The Digital Frontier of Circularity

Education for Plastic Waste Prevention in a Circular Economy

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A Starter Kit for Higher Education Institutions Teachers

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Published by ToKnowPress
Bangkok · Celje · Lublin · Malta
2026

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ToKnowPress is a Joint Imprint of
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International School for Social and Business Studies, Celje, Slovenia
Maria Curie-Sklodowska University, Lublin, Poland
MED.E.A. – Higher Education Institution for Mediterranean, Europe and Africa, Malta

www.toknowpress.net

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The publication of the monograph was financially supported by the Slovenian Research and Innovation Agency

ISBN 978-83-65020-55-0 (printed)
ISBN 978-83-65020-56-7 (pdf)

Distributed free of charge

CC BY-SA https://doi.org/10.53615/978-83-65020-56-7

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Foreword

We live in a plastic world … and plastic circularity has become a local, national and global emergency together with the initiatives for climate neutral. This is the motto that guided our creative and synergistic energies in the development of this book.

In the current context of a very high level of production, but also of the consumption of plastics (in various forms) we are aware that the multifunctionality of plastics means that they will continue to be omnipresent in our lives and in the environment in which we live (air, water, soil). In this context, the need to act in accordance with the circular economy and to mitigate their climate (and environmental) impact is imposed, by educating and raising awareness of responsible consumption (reducing and eliminating the unsustainable consumption that we have created). Our perception, as users and consumers, of plastics has changed in recent years, leading to an exaggerated, chaotic consumption that has become a threat given the effects of plastic pollution and toxicity. All these chain phenomena have forced us to carefully rethink the way we use plastics … but we still have a lot to learn and do because air, water and soil pollution have reached worrying levels, and the effects on life are already proven by medical research.

However, we believe that we must address not only individual consumption behaviour and behavioural patterns, but more urgently the underlying norms and power relations that support and maintain unsustainable levels of plastic consumption. Specialized literature and the real economy have proven that cheap raw materials and abundant fossil fuels have contributed to stimulating our plastic consumption patterns. Thus, to eliminate the carbon footprint of plastics, an important consideration is to make plastic more valuable both in people's minds and throughout the value chain … and *this can only be achieved through education!*

The variety of shapes and structures of plastics is significant, and their widespread use in many areas generates diverse legislative and regulatory provisions, for example in the field of climate, environment, various industries such as automotive, construction, textiles, chemicals, trade and waste management. We are thus witnessing a frag-

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

mentation of the legislative framework and uncoordinated measures around the production, use and recycling of plastics. However, two policy trends have emerged: market restrictions for single-use plastics and the transition to a circular plastics economy. The first is evident in the growing number of policies aimed at reducing plastic pollution by banning certain items, such as plastic bags or straws. The second can address several challenges related to plastics, such as resource inefficiency, as well as environmental and climate impacts. Furthermore, the circular economy is shaping plastics policies, particularly through EU105 and Chinese106 provisions and among non-state actors.

The current sustainability issues, highlighted by the contemporary plastic crisis that is set to intensify in the coming years, are priorities for a growing number of actors and initiatives; however, the ambitions and objectives of these initiatives and strategies fail to mitigate the negative impact of plastics on the climate, as they tend to focus on mitigating plastic pollution.

The plastics value chain is much more complex compared to other energy- and emission-intensive material industries. This is due to the large variety of interconnected processes and companies in petrochemical clusters, as well as the great diversity of plastics and the ubiquity of short- and long-life products in all areas of the economy. In conclusion, the dependence on fossil fuels is extremely strong. This complexity of the value chain, including uncertainty regarding the effectiveness of measures and conflicts of interest between value chain actors, constitute barriers that hinder the vision of a zero-emission future, but also the path to follow towards this goal. Furthermore, the accelerating environmental challenges of our time, particularly those related to plastic production, consumption, and waste, demand not only technological innovation but also a profound transformation in how we think, learn, and act. This book, *The Digital Frontier of Circularity,* emerges as a timely and necessary contribution to this global discourse. We consider it as a valuable starter kit for higher education institutions teaching staff.

Developed within the framework of the EDU4 PlastiCircular project, this book reflects a collective effort to bridge the gap between scientific knowledge, educational practice, and societal needs. It recognizes that the transition from a linear to a circular economy is not merely a technical shift, but a deeply educational one, requiring new competencies, interdisciplinary thinking, and a redefinition of human-environment

relationships. What makes this book particularly valuable is its integrative perspective. It does not treat plastic waste as an isolated environmental issue, but situates it within broader systems of production, consumption, policy, and education. By combining insights from research, pedagogy, and real-world initiatives, the editors and contributors offer a comprehensive resource that speaks to educators, researchers, policymakers, and practitioners alike. A central strength of this work lies in its emphasis on education as a catalyst for change. The chapters highlight *innovative pedagogical approaches,* from experiential learning and citizen science to digital platforms and gamification, that empower learners to actively engage with complex sustainability challenges. In doing so, the book moves beyond awareness-raising to foster critical thinking, practical skills, and behavioural transformation.

Equally important is the book's *focus on digitalization as an enabler of circularity.* In an increasingly interconnected world, digital tools and platforms provide unprecedented opportunities to scale knowledge, facilitate collaboration, and support lifelong learning. The EDU4PlastiCircular initiative demonstrates how digital environments, open educational resources, and international partnerships can enhance accessibility and impact across diverse educational contexts.

The international and collaborative nature of this project further enriches the book's contribution. Drawing on experiences from multiple European countries and institutions, it reflects a shared commitment to addressing plastic pollution through education and innovation. This cross-border perspective underscores the global nature of the problem and the need for coordinated inclusive solutions.

Importantly, this book does not shy away from acknowledging the challenges ahead. Institutional barriers, resource constraints, and knowledge gaps remain significant obstacles to integrating circular economy principles into education systems. Yet, by identifying these challenges and offering evidence-based recommendations, the authors provide a clear pathway forward. In essence, this volume serves as both a guide and an inspiration. It equips higher education institutions and educators with practical tools and conceptual frameworks, while also inviting readers to rethink their role in shaping a more sustainable and circular future. As we stand at a critical juncture for our planet, works like this remind us that education is not only about transmitting knowledge, but also about enabling transformation. *The journey toward a circular and climate-neutral economy begins in classrooms, laborato-*

ries, communities, and digital spaces. This book is a meaningful step in that journey!

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https://doi.org/10.53615/978-83-65020-56-7/7-10

Acknowledgments

The content of the present book has been developed in the context of the EDU4PlastiCircular (Education for Plastic in a Circular and Climate Neutral Economy – Preventing Waste Ending Up into the Environment, 2023-1-RO01-KA220-HED-000166242) project implementation (https://microplastics.today/) co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

We would like to express our sincere gratitude to all anonymous reviewers (from our universities and external reviewers from companies) who generously contributed their time and expertise to provide valuable and innovative ideas that have been contributed to the book content development. Their valuable insights and feedback have significantly enriched and extended our ideas and innovated our approach for developing this starter-kit.

Chapter One

Introduction to Education for a Circular and Climate-Neutral Future: EDU4PlastiCircular Outcomes

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https://doi.org/10.53615/978-83-65020-56-7/11-35

Introduction

We live in a world of plastic, surrounded by countless plastic objects of various types that impact not only our bodies and health, but also the environment we live in. *We are witnessing a global plastic waste crisis that represents one of the most pressing environmental challenges of the 21st century, with an estimated 8 million tons of plastic polluting our waters annually, as well as other categories of nano/microplastics detected in every ecosystem on Earth.* The persistence of plastics in the environment, combined with insufficient waste management systems, has resulted in widespread contamination of terrestrial, aquatic, and atmospheric systems, including the accumulation of microplastics with documented ecological and potential human health implications (Geyer et al., 2017; United Nations Environment Programme, 2021).

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

The transition from a linear 'take-make-throw' model to a circular economy framework has emerged as a critical strategy for addressing plastic pollution while maintaining economic viability. Circularity in plastics is a solution that could save us, ourselves and our planet (Davis, 2022; Islam, 2025; Stathatou et al., 2025).

However, this transition requires fundamental changes in knowledge, attitudes and behaviours at all levels of society, positioning education as a cornerstone of systemic change (Calleja, 2019; Giurea et al., 2025; Draghici et al., 2024). At the same time, educational initiatives for the circular economy and plastic circularity have proliferated globally in the last decade, covering formal education systems, community programmes and vocational training. These initiatives aim to develop 'green skills/competences' and promote responsible environmental practices through various pedagogical approaches (Dermol & Dermol, 2024; Školnik Škrabe & Bubik, 2024).

At the same time, the expansion of digital technologies in education has reshaped instructional delivery and learning environments. E-learning platforms and digital classrooms enable flexible access to content, support multimodal interaction, and facilitate data-informed feedback processes (Means et al., 2014). Nevertheless, evidence suggests that the effectiveness of e-learning depends on the alignment between technological tools and pedagogical design, particularly in domains that require higher-order thinking, problem solving, and behavioural change (Laurillard, 2012). In sustainability education, digital environments must therefore support not only knowledge acquisition but also experiential learning, critical reflection, and action-oriented competencies.

In the context of the present chapter, we aim to provide a comprehensive literature review on educational initiatives for responsible practices in circular economy and plastic circularity based on synthesizes evidence from 90 scholarly publications to: (1) characterize the landscape of educational initiatives in circular economy and plastic circularity; (2) examine the EDU4PlastiCircular project and similar initiatives in depth; (3) identify effective pedagogical approaches and their outcomes; (4) analyse challenges and barriers to implementation; and (5) provide evidence-based recommendations for future educational interventions. The review addresses a critical gap in understanding how education can accelerate the transition toward responsible plastic management and circular economy practices. These are

preliminary aspects to understand the importance and motivation of the EDU4PlastiCircular project, and the training and certification program created via the Erasmus+ funded.

Education for a Circular and Climate-Neutral Future: A Literature Review

The circular economy represents a systemic approach to economic development designed to benefit businesses, society, and the environment by decoupling economic growth from resource consumption (Calleja, 2019; Davis, 2022; Islam, 2025). Unlike the linear economy model, circular systems aim to eliminate waste through superior design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. *The European Union has positioned circular economy as central to its Green Deal, projecting potential economic benefits of up to 1.8 trillion Euros by 2030 while preserving natural resources* (Mulita, 2023; Giurea et al., 2025).

In the context of the plastics world development, circularity encompasses the entire lifecycle from design and production through consumption, collection, and end-of-life management. The 'New Plastics Economy' vision emphasizes that circular approaches must address not only recycling but also prevention of plastic leakage into the environment, particularly microplastics that pose significant ecological and health risks (Vlad at al., 2022; Giurea et al., 2025; Dermol & Dermol, 2024). However, *achieving plastic circularity faces substantial technical, economic, and behavioural challenges, with European plastic packaging waste recycling rates remaining low in many countries and overall post-consumer plastic waste recycling at only 8.51% higher in 2020 than 2018* (Davis, 2022; Islam, 2025; Mulita, 2023).

Education for sustainability has evolved from traditional environmental education to encompass broader social, economic, and cultural dimensions of sustainable development. Contemporary frameworks emphasize transformative learning that challenges existing mental models and fosters critical thinking about consumption patterns and environmental responsibility (Hamid et al., 2024). *The integration of circular economy principles into education represents a relatively recent development, with growing recognition that achieving circularity requires not only technological innovation but also fundamental shifts in knowledge, values, and behaviours* (Dermol & Dermol, 2024).

Several theoretical frameworks underpin circular economy educa-

tion. Experiential learning theory emphasizes hands-on engagement with real-world problems, enabling learners to construct knowledge through direct experience (Draghici et al., 2024). Transformative learning approaches focus on fostering critical reflection and perspective transformation regarding sustainability challenges. *Social learning theory highlights the importance of collaborative knowledge construction and community engagement in driving behavioural change.* These frameworks converge on the principle that effective circular economy education must be active, participatory, and contextually relevant rather than purely didactic (Dermol & Dermol, 2024).

Microplastics (plastic particles smaller than 5mm) have emerged as a particularly concerning dimension of plastic pollution due to their ubiquity, persistence, and potential impacts on ecosystems and human health. These particles originate from both primary sources (microbeads in cosmetics, industrial pellets) and secondary fragmentation of larger plastic items (Školnik Škrabe et al., 2025). Educational initiatives increasingly recognize the need to address microplastics awareness alongside broader circular economy principles, as microplastic pollution represents both a consequence of inadequate waste management and a driver for systemic change (Vlad at al., 2022; Giurea et al., 2025; Dermol & Dermol, 2024).

Research indicates that microplastics contamination affects marine biodiversity, enters food chains, and poses potential risks to human health through ingestion and inhalation. The complexity of microplastics issues, spanning chemistry, ecology, public health, and policy, necessitates interdisciplinary educational approaches that can bridge scientific understanding with practical action (Školnik Škrabe et al., 2025). Citizen science has emerged as a particularly effective methodology for microplastics education, enabling public participation in data collection while building awareness and scientific literacy (Vlad at al., 2022; Giurea et al., 2025; Dermol & Dermol, 2024).

Key Pedagogical Approaches in Circular Economy Education

The complexity of circular economy and plastic waste challenges has led to the adoption of pedagogical approaches that emphasize active, contextualized, and competence-oriented learning.

Transformative Learning

Transformative learning, conceptualized by Jack Mezirow (Mezirow, 1991, 2000), refers to a process through which individuals critically

examine and revise their existing frames of reference-comprising beliefs, assumptions, and values-leading to more inclusive, discriminating, and integrative perspectives. The process unfolds through a sequence of interrelated phases that structure cognitive, affective, and behavioural transformation, consisting of ten core steps, briefly presented below.

The initial phase is the *disorienting dilemma,* which represents a triggering event or experience that exposes inconsistencies between prior assumptions and new realities. In educational contexts, such dilemmas may arise from exposure to complex socio-environmental problems (e.g., plastic pollution or climate change), generating cognitive dissonance and prompting reflective engagement.

This is followed by *self-examination,* often accompanied by emotional responses such as uncertainty or discomfort. Learners begin to interrogate their own beliefs and values, particularly those that have been previously internalized without critical scrutiny. Subsequently, learners engage in a *critical assessment of assumptions,* wherein they analyse the socio-cultural, epistemological, and ethical foundations of their viewpoints. This stage is central to transformative learning, as it enables the deconstruction of taken-for-granted perspectives.

The process then extends into a social dimension through the *recognition of shared experiences,* where individuals realize that others have undergone similar transformations. This intersubjective validation reinforces the legitimacy of questioning dominant paradigms and supports the co-construction of knowledge.

Building on this, learners proceed to the *exploration of new roles, relationships, and actions,* considering alternative ways of thinking and acting. In engineering education, this may involve shifting from linear production models to circular or regenerative approaches. The subsequent phase, *planning a course of action,* entails the formulation of strategies to operationalize these new perspectives.

To support implementation, learners engage in *acquiring knowledge and skills* relevant to their intended transformation. This phase integrates both technical competencies and ethical reasoning capacities. The next stage, *provisional trying of new roles,* involves experimentation in real or simulated contexts, allowing learners to test and refine their emerging perspectives.

As learners gain experience, they develop *competence and self-confidence in new roles,* supported by feedback and reflective practice. The final phase, *reintegration into life with a transformed perspective,* signi-

fies the internalization of new frames of reference, which are then consistently applied across personal and professional domains.

Transformative learning is a recursive and iterative process rather than a strictly linear sequence. Its relevance in sustainability-oriented education lies in its capacity to facilitate deep shifts in mindset, enabling learners to move from passive acceptance of existing systems toward critical, responsible, and action-oriented engagement with complex environmental challenges. Thus, transformative learning is particularly relevant because it addresses entrenched assumptions about resource use, habitual consumption patterns, limited awareness of systemic impacts. Empirical studies indicate that transformative learning is facilitated by experiences that challenge existing perspectives, followed by reflection and discourse (Taylor, 2007). This aligns with educational needs in circular economy, where learners must reconsider linear models of production and consumption.

Experiential and Hands-On Learning

Experiential learning theory conceptualizes learning as a cycle involving concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984). In environmental and engineering education, experiential approaches have been shown to improve understanding of complex processes and enhance retention (Kolb & Kolb, 2005).

Experiential learning approaches that engage students in practical, hands-on activities have emerged as particularly effective for circular economy education. In the context of plastic waste management, experiential learning includes laboratory experiments and investigations (e.g., material properties, microplastics identification), field observations, internships, applied problem-solving tasks. These activities enable learners to connect theoretical concepts with observable phenomena and professional contexts. A notable example from tertiary design education involved students creating innovative products from recycled university plastic waste, specifically HDPE milk bottles, requiring them to design and construct machinery for plastic processing (Nguyen, 2023; Dermol & Dermol, 2024; Hamid et al., 2024). This approach fostered environmental awareness and critical thinking while providing tangible experience with circular economy principles in practice (Vlad at al., 2022; Giurea et al., 2025; Školnik Škrabe et al., 2025).

Community-based initiatives have similarly emphasized hands-on engagement, such as programs involving plastic waste collection, sorting, and creative recycling into economically valuable products. These interventions demonstrate that experiential learning can simultaneously build knowledge, develop practical skills, and foster environmental responsibility. The integration of design thinking and problem-solving challenges enables learners to grapple with the complexity of circular economy systems while developing creative solutions (Giurea et al., 2025; Dermol & Dermol, 2024).

Educational programs incorporating practical waste management activities have shown measurable impacts on knowledge, attitudes, and behaviours. For instance, initiatives involving students in establishing recycling systems within their schools or communities have demonstrated effectiveness in fostering long-term behavioural change and environmental stewardship. The hands-on nature of these activities appears to enhance learning retention and motivation compared to purely theoretical instruction (Nguyen, 2023; Dermol & Dermol, 2024; Školnik Škrabe et al., 2025).

Citizen Science and Participatory Approaches

Citizen science has emerged as a powerful pedagogical approach for microplastics and plastic pollution education, enabling public participation in scientific research while building awareness and scientific literacy (Popa et al., 2022).

Programs engaging students and community members in microplastics sampling, identification, and data collection have proliferated globally, spanning marine, freshwater, and terrestrial environments. These initiatives demonstrate that citizen science can simultaneously contribute to scientific knowledge and serve educational objectives (Giurea et al., 2025; Dermoil & Dermol, 2024; Draghici et al., 2024; Chigwada & Tekere, 2026).

A creative-motivated citizen science after-school STEAM program focused on oceanic microplastics successfully engaged students in addressing this complex environmental problem through hands-on investigation. Similarly, high school students participating in coastal ecosystem monitoring contributed valuable data on marine litter distribution while developing scientific skills and environmental awareness. These examples illustrate how citizen science can bridge formal and informal education while fostering authentic scientific engage-

ment (Popa et al., 2022; Nguyen, 2023; Školnik Škrabe et al., 2025; Chigwada & Tekere, 2026).

The participatory nature of citizen science approaches aligns with social learning theory, emphasizing collaborative knowledge construction and community engagement. Programs involving multiple stakeholder groups, students, teachers, families, and community members, have demonstrated enhanced impact through broader social networks and shared learning experiences. The development of standardized protocols and digital platforms has facilitated scaling of citizen science initiatives while maintaining data quality (Dermol & Dermol, 2024).

Digital and Online Learning Platforms

Digital education platforms have expanded access to circular economy education, particularly important given the global nature of plastic pollution challenges. The development of asynchronous online courses, such as the DIGITOOL to CE (2021–2024) e-learning course on Circular Economy and Green Business, demonstrates the potential for flexible, self-paced learning that accommodates diverse student needs. These platforms utilize modern authoring tools like Adobe Captivate to create interactive content supported by Learning Management Systems (Atstaja et al., 2023).

Online education for circular economy has been analysed for content and didactical approaches, revealing diverse strategies for engaging learners in plastic waste management topics. Digital platforms enable integration of multimedia resources, interactive simulations, and virtual laboratories that can complement or substitute for physical hands-on activities. The COVID-19 pandemic accelerated adoption of digital learning modalities, providing valuable insights into effective online pedagogy for sustainability education (Dermol & Dermol, 2024; Draghici et al., 2024).

However, research from the EDU4PlastiCircular project indicates that online learning was the least preferred format among students and staff, suggesting that purely digital approaches may face engagement challenges. Hybrid models combining online and face-to-face elements appear to offer optimal balance, leveraging digital flexibility while maintaining interpersonal interaction valued by learners. The development of digital pedagogical competences among educators has been identified as essential for effective online circular economy education (Draghici et al., 2024; Školnik Škrabe et al., 2025).

Serious Games and Gamification

Serious games designed for circular economy education have demonstrated significant effectiveness in engaging learners, enhancing retention, and fostering systems thinking by allowing players to interact with complex scenarios, such as resource scarcity and waste management, in a safe, simulated environment. These games often simulate the transition from a linear 'take-make-sell-dispose' model to a circular one, providing hands-on experience with circular business models like repair, reuse, and product-service systems (Roba et al., 2021; Manshoven & Gillabel, 2021).

Research on serious game implementation for circular economy education has identified key success factors including clear learning objectives, appropriate challenge levels, and integration with broader curriculum. Gamification elements such as points, badges, and leaderboards can enhance motivation, but their effectiveness depends on thoughtful design aligned with educational goals rather than superficial game mechanics. The social dimension of multiplayer or collaborative games can foster discussion and shared learning about circular economy principles (Dermol & Dermol, 2024).

Key benefits and effectiveness on using gamification and serious games approaches in the circular economy are summarized in the following (Roba et al., 2021):

- *Enhanced engagement and motivation.* Serious games are more engaging than traditional, passive teaching methods, using competition, collaboration, and rewards to increase participation.
- *Systems thinking.* Games help players understand the interconnectedness of decisions regarding resource management, company profits, and environmental impact.
- *Improved retention.* By 'learning-by-doing,' participants better remember complex CE strategies and their consequences in a simulation.
- *Visualization of complex concepts.* Games provide tangible representations of abstract concepts like material flows, resource exhaustion, and waste, turning complex systems into understandable, interactive experiences.
- *Simulated consequences.* Players can experience the long-term impacts of their decisions on company profitability and resilience

against external events such as policy changes or resource shortages.

Transdisciplinary and Integrated Approaches

Effective circular economy education increasingly adopts transdisciplinary approaches that integrate knowledge from natural sciences, engineering, social sciences, economics, and humanities. The complexity of circular economy challenges (spanning technical, economic, social, and policy dimensions) necessitates educational approaches that transcend traditional disciplinary boundaries. Integration of circular economy principles into STEM education has been identified as a promising pathway toward developing 'circular citizenship' (Nguyen, 2023; Dermol & Dermol, 2024).

Transdisciplinary approaches emphasize co-production of knowledge with stakeholders beyond academia, including industry, government, and civil society. This stakeholder engagement enriches learning by connecting theoretical concepts with real-world applications and constraints. Educational initiatives involving partnerships between universities, businesses, and communities have demonstrated enhanced relevance and impact compared to purely academic programs. The integration of circular economy concepts across multiple subjects and grade levels, rather than as isolated topics, has been advocated as essential for developing comprehensive understanding. For instance, circular economy principles can be incorporated into chemistry education through focus on materials and recycling processes, into economics through business model innovation, and into social studies through policy and behavioural dimensions. This integrated approach helps students recognize interconnections and develop systems thinking capabilities (Dermol & Dermol, 2024; Školnik Škrabe et al., 2025).

Educational Initiatives Across Different Contexts

Higher Education Initiatives

Higher education institutions have emerged as critical sites for circular economy education, with initiatives ranging from specialized courses to comprehensive curriculum reform. Universities are developing innovative curricula to drive the EU Green Deal through education on circular economy and green business, recognizing their role in preparing future professionals and leaders. The integration of sustainability

and circular economy into teacher training programs has been identified as particularly strategic, as educators can multiply impact through their teaching (Bugallo-Rodríguez et al., 2020; Draghici et al., 2024).

Sustainability in plastics curriculum has been specifically addressed in engineering and materials science programs, with focus on training for improving plastics circularity. These initiatives integrate technical knowledge about plastic materials, processing, and recycling with broader circular economy principles and sustainability considerations. Case studies from universities implementing circular economy practices for plastic waste management demonstrate how institutions can serve as living laboratories for sustainability (Giurea et al., 2025). Challenges in higher education include curriculum rigidity, limited interdisciplinary collaboration, and insufficient integration of practical experience with theoretical knowledge. Research indicates that while students may understand basic circular economy principles, they often lack deeper comprehension of waste management hierarchies and practical implementation strategies. Professional development for faculty has been identified as essential for overcoming these barriers and enabling effective circular economy education (Dermol & Dermol, 2024; Školnik Škrabe et al., 2025).

Primary and Secondary Education

Educational initiatives in primary and secondary schools have employed diverse approaches to foster circular economy awareness and responsible plastic management behaviours. Pedagogical strategies emphasizing critical reflection have been implemented to raise awareness about solid plastic waste management in educational communities, promoting sustainable development objectives and environmental responsibility. These initiatives often involve the entire educational community including students, teachers, and parents to maximize impact.

Environmental education programs focused on plastic waste reduction have demonstrated measurable effects on student awareness and practices. For instance, programs implementing the 3R principles (Reduce, Reuse, Recycle) through hands-on activities and creative projects have successfully engaged students while developing practical skills. The integration of circular economy concepts into existing curricula, rather than as separate add-on topics, has been advocated for sustainable implementation (Giurea et al., 2025).

Secondary school students' understanding of circular economy and recycling has been investigated in various contexts, revealing both opportunities and challenges. While students often demonstrate basic awareness of environmental issues, deeper understanding of circular economy systems and their role as consumers within these systems requires targeted educational intervention. Small rural schools face particular challenges including limited resources and teacher expertise, though they may benefit from strong community connections (Laius et al., 2024).

Community-Based and Informal Education

Community-based educational initiatives have proven effective for engaging diverse populations in circular economy and plastic waste management. Programs empowering local communities through education and recycling solutions have demonstrated that combining knowledge building with practical action can drive behavioural change and community-level impact. These initiatives often emphasize the economic value of recycled materials, providing motivation through both environmental and livelihood benefits (Widiastuti et al., 2023).

Informal education through outreach programs, workshops, and awareness campaigns has reached audiences beyond formal educational systems. For instance, chemistry outreach programs on circular plastic economy have engaged secondary students and teachers, demonstrating effectiveness of targeted, topic-specific interventions. The flexibility of informal education enables adaptation to local contexts and specific community needs (Widiastuti et al., 2023).

Educational contests and competitions have been employed to engage students and communities in transitioning 'from linear to circular ideas,' fostering creativity and innovation in addressing circular economy challenges. These initiatives leverage intrinsic motivation and social recognition to encourage participation and learning. Community-based approaches often emphasize social cartography, participatory mapping, and other tools that enable communities to analyse their own waste management challenges and develop locally appropriate solutions (Velis et al., 2022).

Professional and Vocational Training

Professional and vocational education for circular economy has been recognized as essential for developing workforce capacity to imple-

ment circular systems. Technical and vocational education institutions are increasingly incorporating circular economy concepts, though systematic literature reviews indicate this integration remains limited and uneven. The development of green skills through professional training addresses industry demand for workers capable of implementing circular economy practices (Widiastuti et al., 2023; Laius et al., 2024; Hamid et al., 2024).

Circular economy education in professional contexts must balance theoretical understanding with practical competencies relevant to specific industries and occupations. For the plastics sector, this includes technical knowledge of materials, processing technologies, recycling methods, and quality control, as well as broader understanding of circular business models and supply chain management. Professional training programs have been developed to address specific circular economy challenges such as plastic packaging waste management and closed-loop systems (Velis et al., 2022; Giurea et al., 2025; Hamid et al., 2024).

The informal recycling sector represents a significant but often overlooked dimension of circular economy workforce, particularly in low- and middle-income countries. Educational and capacity-building initiatives targeting informal recyclers can enhance material quality, improve livelihoods, and reduce plastic pollution while supporting inclusive circular economy. These interventions must address not only technical skills but also safety, organization, and market access (Velis et al., 2022; Widiastuti et al., 2023; Hamid et al., 2024).

International and Cross-Cultural Initiatives

International collaboration in circular economy education has been facilitated through programs such as Erasmus+ and Horizon Europe, enabling knowledge exchange and capacity building across countries. The EDU4PlastiCircular project exemplifies this international approach, bringing together partner institutions from multiple European countries to develop shared educational resources and approaches. Cross-cultural initiatives must navigate differences in educational systems, environmental priorities, and cultural contexts while identifying universal principles (Draghici et al., 2024).

Educational initiatives have been documented across diverse geographical contexts including Europe, Asia, Latin America, and Africa, each adapting circular economy principles to local circumstances.

For instance, educational programs in Thailand have integrated circular plastic economy into chemistry curriculum with focus on smart cities and zero plastic leakage. Latin American initiatives have emphasized community participation and social justice dimensions of circular economy (Kruja et al., 2025).

Key pedagogical approaches adopted by many trainers and professors in different educational programs dedicated to circular economy and plastic waste management have increasingly used *team-based, project-based, and collaborative learning* to connect academic curricula with real-world problems. This includes (Nguyen, 2023; Kruja et al., 2025):

- *STEM integration.* Using Science, Technology, Engineering, and Math to design school curricula that solve environmental problems.
- *Real-world context.* Using 'living labs' and community-based projects to turn schools into models of a circular economy

The global nature of plastic pollution necessitates international coordination in education as well as policy and practice. International frameworks such as the UN Sustainable Development Goals and the UN Decade of Ocean Science for Sustainable Development provide common reference points for educational initiatives worldwide. Ocean literacy and blue curricula initiatives supported by the EU Mission Ocean demonstrate how international programs can enhance educational networks and promote shared approaches (Mulita, 2023).

Key Findings from the Literature Review and Comparative Analysis

Effectiveness of Educational Interventions

Educational interventions for circular economy and plastic circularity have demonstrated measurable impacts on knowledge, attitudes, and behaviours across diverse contexts. Studies employing pre-post assessment designs have documented significant increases in understanding of circular economy principles, plastic pollution impacts, and waste management practices following educational interventions. However, the magnitude and persistence of these effects vary considerably depending on intervention design, duration, and context (Hamid et al., 2024; Draghici et al., 2024; Dermol & Dermol, 2024).

Hands-on, experiential approaches consistently lead to better learning outcomes than purely didactic instruction. Programs involving students in practical activities such as waste audits, recycling projects, or product design from recycled materials show enhanced knowledge retention and behavioural change. The active engagement and personal relevance of experiential learning appear to foster deeper understanding and motivation for sustainable practices (Bugallo-Rodríguez et al., 2020; Dermol & Dermol, 2024).

Citizen science initiatives have proven particularly effective for fostering both scientific literacy and environmental awareness regarding microplastics and plastic pollution. Participants in citizen science programs demonstrate increased understanding of scientific methods, enhanced critical thinking skills, and stronger environmental stewardship attitudes. The authentic nature of contributing to real scientific research appears to enhance motivation and learning compared to simulated activities (Popa et al., 2023; Školnik Škrabe & Bubik, 2024; Školnik Škrabe et al., 2025).

Common Themes and Patterns

Several common themes emerge across successful educational initiatives for circular economy and plastic circularity. First, effective programs emphasize systems thinking, helping learners understand interconnections between production, consumption, waste management, and environmental impacts. Second, successful initiatives balance knowledge building with practical skills development and behavioural change objectives. Third, stakeholder engagement and community participation enhance both learning outcomes and real-world impact (Dermol & Dermol, 2024).

The integration of economic and environmental dimensions appears critical for fostering comprehensive understanding of circular economy. Programs that address only environmental impacts without considering economic viability and business models may fail to prepare learners for real-world implementation challenges. Conversely, initiatives emphasizing economic opportunities of circular economy, such as job creation, cost savings, and innovation, can enhance motivation and perceived relevance (Giurea et al., 2025; Školnik Škrabe et al., 2025).

Cultural and contextual adaptation emerges as essential for effective circular economy education across diverse settings. While core circular economy principles remain consistent, successful initiatives

adapt pedagogical approaches, examples, and emphasis to align with local environmental priorities, cultural values, and educational systems. This balance between universal principles and local relevance appears critical for engagement and impact (Kruja et al., 2025).

Target Audience Considerations

Educational initiatives demonstrate distinct characteristics and challenges depending on target audience. Higher education programs can address complex technical and theoretical content but may struggle with curriculum integration and interdisciplinary collaboration. Primary and secondary education initiatives must balance age-appropriate content with meaningful engagement, often emphasizing hands-on activities and creative expression. Community-based programs for general public require accessible language and clear connections to daily life and local concerns (Bugallo-Rodríguez et al., 2020; Draghici et al., 2024).

Professional and vocational training must prioritize practical competencies and industry relevance, often requiring partnerships with businesses and industry associations. Teacher training programs serve a multiplier function, as educators can integrate circular economy principles into their ongoing teaching, but require sustained support and resources. Policymaker education focuses on evidence synthesis, policy instruments, and systemic change strategies rather than technical details (Hamid et al., 2024; Dermol & Dermol, 2024; Draghici et al., 2024)

Intergenerational and whole-community approaches that engage multiple audiences simultaneously have demonstrated enhanced impact through social learning and mutual reinforcement. Programs involving students, teachers, parents, and community members create broader social networks for knowledge sharing and behavioural change. This multi-audience approach aligns with recognition that achieving circular economy requires coordinated action across society rather than isolated individual changes (Nguyen, 2023; Dermol & Dermol, 2024).

Geographic and Cultural Variations

Educational initiatives in European contexts often emphasize policy frameworks such as the EU Green Deal and Circular Economy Action Plan, reflecting the strong policy drivers in this region. European pro-

grams frequently involve international collaboration through mechanisms like Erasmus+ and Horizon Europe. Asian initiatives often integrate circular economy with smart city development and technological innovation. Latin American programs frequently emphasize social justice, community empowerment, and informal sector inclusion. Resource availability and infrastructure significantly influence educational approaches, with high-income countries more likely to implement technology-intensive solutions such as advanced digital platforms or sophisticated recycling equipment. Low- and middle-income countries often emphasize community-based approaches, informal sector engagement, and low-cost solutions. However, innovation occurs across all contexts, with valuable lessons emerging from resource-constrained settings that develop creative, locally appropriate solutions (Draghici et al., 2024; Giurea et al., 2025; Školnik Škrabe et al., 2025).

Cultural values regarding waste, consumption, and environmental responsibility shape both educational content and pedagogical approaches. Collectivist cultures may emphasize community benefits and social responsibility, while individualist cultures may focus more on personal choice and individual impact. Effective educational initiatives recognize and work within these cultural frameworks rather than imposing external values (Nguyen, 2023; Kruja et al., 2025).

Challenges and Barriers to Implement Education for Circular Economy and Plastic Circularity

Institutional and Systemic Barriers

Curriculum rigidity and institutional inertia represent significant barriers to integrating circular economy education into formal educational systems. Established curricula with fixed content requirements and assessment structures leave limited flexibility for introducing new topics or interdisciplinary approaches. Institutional resistance to change, particularly in higher education, can slow adoption of innovative pedagogical approaches even when faculty and students' express interest (Draghici et al., 2024; Giurea et al., 2025).

Limited interdisciplinary collaboration within educational institutions constrains development of comprehensive circular economy education. Traditional disciplinary silos separate technical, economic, social, and policy dimensions of circular economy, hindering systems thinking development. Institutional structures including departmen-

tal organization, funding mechanisms, and promotion criteria often discourage rather than reward interdisciplinary teaching and research (Stathatou et al., 2025; Giurea et al., 2025).

Lack of managerial support and inadequate resources have been identified as critical barriers to implementing circular economy education. Even motivated educators may struggle to develop and deliver effective programs without institutional backing, funding for materials and activities, and time allocation. Infrastructure limitations including inadequate facilities for hands-on activities or recycling demonstrations constrain practical learning opportunities (Draghici et al., 2024; Dermol & Dermol, 2024).

Knowledge and Capacity Gaps

Limited teacher knowledge and confidence regarding circular economy concepts represents a fundamental barrier to effective education. Many educators lack formal training in sustainability, circular economy, or plastics science, constraining their ability to teach these topics effectively. Professional development opportunities remain insufficient to address this capacity gap at scale (Školnik Škrabe et al., 2025; Giurea et al., 2025). The interdisciplinary nature of circular economy challenges educators who may have deep expertise in one domain but limited knowledge of others. For instance, chemistry teachers may understand plastic materials and recycling processes but lack knowledge of circular business models or policy frameworks. Conversely, social science educators may understand behavioural and policy dimensions but lack technical knowledge of materials and processes (Draghici et al., 2024; Dermol & Dermol, 2024).

Students limited prior knowledge and misconceptions about circular economy and plastic pollution can impede learning. Research indicates that while students may have basic awareness of environmental issues, they often lack understanding of circular economy principles, waste management hierarchies, and the complexity of plastic pollution challenges. Addressing these knowledge gaps and misconceptions requires careful pedagogical design and sufficient instructional time (Školnik Škrabe et al., 2025).

Resource and Infrastructure Constraints

Financial constraints limit implementation of circular economy education, particularly for hands-on activities, field trips, equipment, and

materials. Schools and community organizations in resource-limited settings may lack funds for even basic supplies for recycling projects or waste management demonstrations. Higher education institutions may struggle to invest in specialized equipment for plastics processing or analysis (Dermol & Dermol, 2024; Draghici et al., 2024).

Physical infrastructure limitations constrain practical learning opportunities, with many schools lacking adequate facilities for waste sorting, composting, or recycling activities. Laboratory equipment for microplastics analysis or materials testing may be unavailable or prohibitively expensive for educational institutions. Digital infrastructure gaps including limited internet access or devices constrain implementation of online and hybrid learning approaches in some contexts (Školnik Škrabe & Bubik, 2024; Školnik Škrabe et al., 2025).

Time constraints represent a pervasive challenge, with educators reporting insufficient time to adequately address circular economy topics within existing curricula. The pressure to cover mandated content and prepare students for standardized assessments leaves limited flexibility for in-depth exploration of sustainability topics. Hands-on and experiential learning approaches, while effective, require more time than traditional lecture-based instruction (Draghici et al., 2024; Školnik Škrabe et al., 2025).

Engagement and Motivation Challenges

Maintaining student engagement and motivation for circular economy education can be challenging, particularly when topics are presented in abstract or disconnected ways. Students may perceive environmental issues as distant or overwhelming, leading to disengagement or eco-anxiety rather than empowerment. Effective education must balance awareness of problems with emphasis on solutions and agency. The complexity of circular economy systems can be overwhelming for learners, potentially leading to confusion or disengagement. Educational approaches must scaffold learning, building from concrete examples and personal experiences toward more abstract systems thinking. Oversimplification, however, risks conveying misleading impressions about the ease of achieving circular economy (Školnik Škrabe et al., 2025; Giurea et al., 2025).

Cultural and socioeconomic factors influence engagement with circular economy education. Students from communities facing immediate economic pressures may perceive environmental education as

less relevant than more pressing concerns. Effective initiatives connect circular economy to local priorities including economic opportunity, health, and community well-being (Islam, 2025).

Discussion and Implications

Synthesis of Evidence

This literature review reveals a rapidly expanding and increasingly sophisticated field of educational practice and research focused on circular economy and plastic circularity. The EDU4PlastiCircular project and similar initiatives demonstrate growing recognition that education is essential for achieving the systemic changes required to address plastic pollution and transition toward circular economy. The diversity of approaches documented (spanning formal and informal education, different age groups and contexts, and various pedagogical methods) reflects both the complexity of the challenge and the creativity of educators and researchers addressing it.

Several key principles emerge from synthesis of this evidence. First, effective circular economy education must be active and experiential rather than purely didactic, engaging learners in hands-on activities that build both knowledge and practical skills. Second, interdisciplinary and systems-oriented approaches are essential for developing comprehensive understanding of circular economy's technical, economic, social, and policy dimensions. Third, stakeholder engagement and community participation enhance both learning outcomes and real-world impact.

The evidence also reveals significant gaps and challenges. Despite proliferation of initiatives, systematic evaluation of long-term impacts remains limited. Most studies document short-term knowledge gains or attitude changes, but evidence regarding sustained behavioural change and real-world environmental outcomes is scarce. The field would benefit from more rigorous research designs including longitudinal studies, control groups, and measurement of behavioural and environmental outcomes beyond self-reported attitudes.

The Role of Higher Education

Higher education institutions play a critical role in circular economy education through multiple pathways. Universities educate future professionals, policymakers, and educators who will drive circular economy implementation across sectors. Research conducted at universi-

ties generates knowledge about circular economy systems, technologies, and policies. Universities can serve as living laboratories, implementing circular economy practices on campus while using these as learning opportunities for students.

The EDU4PlastiCircular project exemplifies strategic investment in higher education capacity for circular economy education. By focusing on both students and academic staff, the project recognizes that educator capacity is essential for sustainable scaling of educational initiatives. The project's emphasis on green skills development aligns with labour market needs and policy priorities, potentially enhancing graduate employability while addressing environmental challenges (Draghici et al., 2024).

However, higher education faces particular challenges in integrating circular economy education including curriculum rigidity, disciplinary silos, and limited incentives for pedagogical innovation. Overcoming these barriers requires institutional commitment, resource allocation, and systemic changes to academic structures and cultures. The development of interdisciplinary programs, centres, and initiatives focused on circular economy can provide institutional homes for this work.

Scaling and Sustainability of Initiatives

Scaling effective circular economy education from pilot projects to widespread implementation represents a critical challenge. Many documented initiatives remain small-scale, reaching limited numbers of learners and dependent on external funding or individual champion educators. Sustainable scaling requires integration into mainstream educational systems, development of educator capacity at scale, and creation of supportive policy and resource environments.

Digital platforms and open educational resources offer potential pathways for scaling, enabling broader access to high-quality educational materials and reducing development costs. However, the EDU4-PlastiCircular finding that online learning was least preferred among students and staff suggests that purely digital approaches may face engagement challenges. Hybrid models combining online resources with face-to-face interaction may offer optimal balance for scaling while maintaining effectiveness.

International collaboration and knowledge exchange can accelerate scaling by enabling adaptation of successful approaches across contexts rather than requiring each institution or country to develop ini-

tiatives from scratch. Networks such as the European Blue Schools and platforms for sharing circular economy educational resources facilitate this knowledge exchange. However, effective adaptation requires attention to local context rather than simple replication.

Policy Implications

The evidence synthesized in this review has several important policy implications. First, achieving circular economy requires substantial investment in education across all levels and contexts, not merely as an add-on but as a core component of sustainability transitions. Policy frameworks such as the EU Green Deal and Circular Economy Action Plan should explicitly prioritize and resource educational initiatives.

Second, policies should support educator professional development at scale, recognizing that teacher capacity is a fundamental constraint on effective circular economy education. This includes both pre-service teacher education and ongoing professional development for current educators. Interdisciplinary training that bridges technical, economic, social, and policy dimensions of circular economy is particularly needed.

Third, policies should incentivize and support institutional integration of circular economy education rather than relying solely on voluntary initiatives. This includes curriculum frameworks incorporating circular economy, assessment systems valuing sustainability competencies, and funding mechanisms for interdisciplinary, experiential learning. Additionally, rewarding educators who implement innovative circular economy education will drive broader adoption.

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Chapter Two

Navigating the Digital Frontier of Plastic Circularity

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https://doi.org/10.53615/978-83-65020-56-7/37-65

Global Trends in Plastic Production and Use

Plastic production has grown exponentially worldwide in just a few decades. *After a steep decline in the first half of 2020 due to COVID-19, production of plastic recovered in the second half of the year and with-it plastic waste. Under the EU Green Deal, 55% of plastic packaging will have to be recycled by 2030.* This implies innovative design, cleaner production and recyclability initiatives build under the circular and neutral economy principles (as supported by PACE latest reports[1]).

Actual facts and statistics about large plastic waste and low recycling/reuse are shown in the official reports of the European Commission[2] and in the last report.[3] It is impressive that Romania and Italy have a recycling rate of 40–50% (lowest rates), Spain of 50–60% and Slovenia more than 70% due to the efforts in education and awareness of the problem. Furthermore, the global challenge of plastic pollution has reached a critical juncture, with world production growing exponentially from *1.5 million tonnes in 1950 to 359 million tonnes in 2018.* Global consumption of plastics has increased *twentyfold in the last 50 years,* and approximately *40% of these materials are used for packaging,* often characterized by a short lifespan and single-use application. This linear 'take-make-waste' model is economically inefficient, as an estimated *95% of the material value of plastic packaging is lost* after just

[1] See https://pacecircular.org/news
[2] More statistics are provided at https://www.europarl.europa.eu/news/ro/headlines/society/20181212STO21610/deseurile-din-plastic-si-reciclarea-in-ue-in-cifre
[3] https://plasticseurope.org/wp-content/uploads/2022/06/PlasticsEurope-CircularityReport-2022_2804-Light.pdf

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one short use cycle. The environmental and climate consequences are equally severe. In 2019 alone, the production and incineration of plastics generated over *850 million tonnes of greenhouse gases,* a figure projected to rise to 2.8 billion tonnes by 2050. A significant byproduct of this pollution is the accumulation of *microplastics,* defined as small plastic pieces *less than 5 mm (0.2 inch) in length.* These persistent particles originate from various sources, including the wear and tear of *paints (unintentional release), tyres, and synthetic textiles.*

Beyond the packaging sector, the *building and construction industry* is a major consumer of plastic, accounting for approximately *6% of total consumption.* This sector primarily utilizes durable plastics such as *PVC and HDPE* for pipes, interior fittings, and water tanks. However, recycling rates in construction remain alarmingly low, estimated at *less than 1%* in some regions, due to a lack of waste separation at the source and the prioritization of heavier materials like concrete and metal. By aligning with ambitious European goals, such as the *EU Green Deal's target to recycle 55% of plastic packaging by 2030,* this book explores how digital frontiers can be leveraged to *stop plastic waste from entering the natural environment* and secure a sustainable, circular future.

As can be seen, the scale of plastic waste is a significant global and regional challenge, driven by a dramatic increase in production and consumption coupled with historically low recycling and reuse rates. In the following there will be presented more fact and figures related to the plastic waste and pollution, including the micro/nanoplastic by considering the changes and challenges that population and organizations of all type should face.

1. Global and European production and consumption of plastic materials:
   - Exponential growth of plastic production that has surged from 1.5 million tonnes in 1950 to 359 million tonnes in 2018. This fact has supported and has been supported by the massive consumption increases, at the global scale, of plastics materials and parts that has increased twentyfold in the last 50 years (Ackerman & Levin, 2023).
   - In European Union countries, plastic consumption stands out as one of the highest globally, averaging 107 kg per capita annually. Approximately 40% of plastics materials are used for packaging, which is often characterized by a short lifespan and

single-use application. Together with packaging, the building and construction sector accounts for more than half of the total plastic consumption in Europe (Ackerman & Levin, 2023).

- In this context, and considering the current rates, plastic packaging volumes are expected to quadruple by 2050, reaching 318 million tonnes per year.

2. Low recycling and reuse rates of plastic parts, products or other type of waste are recorded in the actual period!
   - In Europe, only nearly one-third of plastic waste is recycled; globally, only about 14% of plastic packaging is even collected for recycling. Thus, practitioners and scientists agree that we are confronting with the recycling gap in the plastic materials! Despite the volume of waste, the demand for recycled plastics in Europe represented only 6% of the total plastic demand in 2018 and it seems that it is of low rate even in 2026. 'Across the European Union countries, people generate roughly 35 kilograms of plastic packaging waste per person each year, but only about 40–42% of that material is recycled. While this represents progress compared to a decade ago, improvement has been slow, and in many countries recycling rates remain well below EU targets. Only a small number of Member States are currently on track to meet the 55% plastic packaging recycling target set for 2030.'[4] Furthermore, the circular material use rate for plastics in the EU, the proportion of recycled material used in new products, was just 8.1% in 2020.
   - 'Recycling only works if manufacturers consistently use recycled plastic in new products. Without stable end-markets, collecting more plastic does not automatically lead to more recycling, and material that cannot be sold is often diverted to incineration instead. In that sense, the plastic recycling problem in 2026 is a systems issue. Without stronger demand for recycled plastics, simpler and more recyclable packaging design, and sufficient domestic processing capacity, higher targets alone are unlikely to deliver meaningful circularity.'[5]

[4] More details at https://www.wastepapertrade.com/blogposts/why-plastic-recycling-is-struggling-in-the-eu-in-2026

[5] See https://www.wastepapertrade.com/blogposts/why-plastic-recycling-is-struggling-in-the-eu-in-2026

- While construction industry is a major user of durable plastics (like PVC and HDPE pipes), its plastic recycling rate is estimated to be less than 1% in some regions, such as Malaysia (Chen et al., 2021; Tan et al., 2022). Even when plastic reaches recycling facilities, losses are high; the actual plastic recyclizes produced are often only about 65% of the total plastic waste that enters the facility.
- The most problematic sector in terms of low plastic waste management is the packaging one (Ncube et al., 2021). 'Plastics overall and packaging as its main application are priority materials within CE strategies, especially in EU policy. However, plastics have currently very low circularity, with less than 20% overall recycling in the EU and around 5% input of secondary streams to closed-loop applications. Moreover, while the understanding of potential environmental effects of large-scale transition to circularity for plastics has improved substantially, socioeconomic implications, and particularly the potential for environment-economy tradeoffs, are understudied' (Cimpan et al., 2023).

3. Economic loss and waste management aspect:
   - The current linear model (take-make-waste) is highly inefficient, with an estimated 95% of the material value of plastic packaging being lost to the economy after a single short use cycle. This lost value is worth approximately 105 billion annually which support the idea of value depletion (Szaky, 2019; Enthaler, 2026).
   - In Europe, 25% of all plastic waste still ends up in landfills. Furthermore, approximately 50% of the plastic collected for recycling in the European Union is exported to countries outside the Union due to a lack of local capacity or resources. Globally, 11% of all plastic waste went uncollected in 2016, and average collection rates in low-income countries remain below 50%. Thus, we assist to a great phenomenon of unmanaged waste (Ackerman & Levin, 2023; Enthaler, 2026).

4. Environmental and climate impact of plastic materials are hot subjects:
   - Over 99% of plastic is manufactured from fossil fuels, contributing significantly to greenhouse gas emissions. In 2019,

global plastic production and incineration released over 850 million tonnes of greenhouse gases into the atmosphere (Ackerman & Levin, 2023).

- The 'wear and tear' of products during use leads to massive unintentional releases of microplastics (pieces less than 5mm). Annual estimated releases in the European Union include:
  - Paints: 231,000 to 863,000 tonnes;
  - Tyres: 360,000 to 540,000 tonnes;
  - Pellets: 52,140 to 184,290 tonnes;
  - Textiles: 1,649 to 61,078 tonnes.

During and after the COVID-19 outbreak, an unprecedented requirement and consumption of plastic materials led to the release of single-use plastic products in the environment, and ever since pyramid of plastic waste in the environment has been burgeoning. It had been estimated that a massive amount of single-use plastic litter had been produced across the globe, with 1.6 million tonnes of PPE (facemasks) and 3.4 billion single-use facemasks being discarded daily during the COVID-19 period (Benson et al., 2021). The Asian continent produced the highest quantity of single-use plastic facemasks (1.8 billion per day), followed by Europe (445 million per day), Africa (411 million per day), Latin America (380 million per day), and North America (244 million/day). This pandemic has also led to an overall surplus increase in plastic pollution, which is also associated with negative impacts on biodiversity and reduced recycling provision. The published reports on global plastic pollution during the COVID-19 times showed short and long-term environmental risks associated with toxic GHG emissions from plastic production and incineration facilities. Due to this sudden boom of plastic pollution and lack of proper management of these plastic wastes, a new pandemic linked to the *plastisphere* may soon be affecting our environment and human health (Sharma et al., 2023).

In the same context, the pyramid of plastic waste in the environment has been burgeoning and there has been proposed and discussed the pyramid of plastic recycling (Figure 2.1) designed with reference to a series of scientific studies detailing the flow of recyclable plastics in Colombia, India, Indonesia, Kenya and South Africa. This general model varies with local recycling infrastructure and institutional context; ecology and sustainability practitioners and scientists support the fact that much plastic waste remains uncollected and unmanaged



FIGURE 2.1 The Pyramid of Plastic Recycling

NOTES Created using ChatGPT, based on Barford and Ahmad (2021).

(Barford & Ahmad, 2021). *The pyramid of plastic recycling* was proposed and designed with reference to a series of studies detailing the flow of recyclable plastics in Colombia, India, Indonesia, Kenya and South Africa. This general model varies with local recycling infrastructure and institutional context; ecology and sustainability practitioners and scientists support the fact that much plastic waste remains uncollected and unmanaged (Barford & Ahmad, 2021).

Furthermore, there is estimated that by 2050, the increased plastic production will be responsible for approximately 13 % of our planet's total carbon budget, equating to 615 coal-fired power station emissions (Hamilton & Feit, 2019; Sharma et al., 2023). In addition, the negative effect of plastic waste pollution has also been great expanded in the 'marine ecosystem, starting from shallow coastal areas to the deepest layers of the aquatic bodies sampled to date and in the most remote and sensitive locations on Earth (Napper & Thompson, 2020). Over the last two decades, marine pollution by plastic debris has been increasing and significantly contributing to global climate change. The impact of climate change is already in place in the form of a sea-level rise, ocean acidification, and extreme weather conditions, leading to socio-economic and ecological harm (Ford et al., 2022). Therefore, intensive

research on the impact of plastic pollution on climate change is the need of the hour so that decision-making agencies can frame mitigation policies to tackle this menace' (Sharma et al., 2023).

Rationale for the EDU4 PlastiCircular Project

In response to these challenges, the EDU4 PlastiCircular Erasmus+ Project was established under the title: Education for Plastic in a Circular and Climate Neutral Economy – Preventing Waste Ending Up into the Environment. This initiative seeks to foster a *climate-neutral economy* by bridging the gap between circular principles and practical educational tools. The project delivers three primary pillars of innovation:

1. *Gathering best practices* regarding the role of plastic in circular and neutral economies and provide a pedagogical base for education in the area;
2. Developing an interactive *e-learning classroom* to effectively disseminate specialized knowledge and to perform massive open online courses (MOOC);
3. Curating a *Digital Library of relevant materials* to provide a centralized hub for researchers and the public (promoting open science and lifelong learning initiatives).

To ensure inclusive education, the project's digital platforms incorporate *accessibility tools,* such as *high-contrast modes and readable fonts,* allowing a diverse range of beneficiaries to engage with the content. The success of this initiative is driven by an international consortium of six partners:

- Universitatea Politehnica Timişoara (Romania), https://www.upt.ro/ – project coordinator;
- Universitat Politecnica de Valencia (Spain), https://www.upv.es/index-en.html;
- Faculty of Environmental Protection Velenje (Slovenia), https://fvo.si/;
- Universitatea Transilvania din Brasov (Romania), https://www.unitbv.ro/;
- Universita degli Studi dell'Insubria (Italy), https://www.uninsubria.it/;



FIGURE 2.2 EDU4 PlastiCircular Consortium Members Logo

- Dermol svetovanje d.o.o. (Slovenia), https://dermol.si/.

EDU4 PlastiCircular is a unique and complex initiative developed by 6 partners from 4 countries supported by local and regional stakeholders committed to fill the existing gap in sustainable development education, management and work practices.

EDU4 PlastiCircular project is perfectly aligned to the European Council recommendation on learning for the green transition[6] and our initiative will provide learners of all ages (HEIS trainers/educators, students and also managers and employees of organizations) with training opportunities about the plastic in circular and climate neutral economy and sustainability (as a strong need!), thus making learning for the green transition a priority of HEIS via the green skills/competencies' development. Through EDU4 PlastiCircular initiative/training programme will enable behavioral changes for trainees/individual preferences, cultural values, awareness, responsible behavior and more generally support active engagement for EU climate neutral till 2050 (started from community, organization, region and country levels). Thus, the project incorporates many green practices/approaches as: green management, green mobilities, online/e-learning solutions, e-books, green pedagogy that will contribute to the green skills and competences development, green awareness, green careers/jobs (as supported by the project work packages content) and finally: green HEIS.

The main target group/target audiance of the course is *adult lifelong learners from EU countries* (aged 18–65), specifically:

- *Managers and employees* of different organizations (particularly

[6] See https://education.ec.europa.eu/news/learning-for-the-green-transition-and-sustainable-development

those who may collaborate with HEIS), who will apply the knowledge acquired from the course to make their organizations and processes greener regarding plastics.
- *HEI teachers/educators* (all categories of teaching staff), who will transfer the knowledge gained from the course to their students. HEIS teaching staff are main beneficiaries of the EDU4PlastiCircular open education resources but also trainers and consultants from business filed could be interested and attract in the training journey.
- *Students* from various engineering education programs, business administration and economics, including learners at different levels (BSC, MSC, PhD), who will be better prepared to manage, address and face future plastic/packaging challenges, plastic circularity strategies and plastic waste.

Digital tools play a fundamental role in ensuring and supporting the *sustainability of education* within the EDU4PlastiCircular project, offering long-term solutions for the dissemination of knowledge about the circular economy. They contribute to several keyways:

- *Accessibility and inclusion.* The project's digital platforms include essential *accessibility tools,* such as text enlargement, readable fonts, high-contrast modes, and light background options. These features ensure that educational resources remain accessible to a diverse range of users indefinitely.
- *Continuity of resources.* Through the creation of an *e-learning classroom* and a *Digital Library,* the project transforms information into a permanent resource. These tools allow beneficiaries to access study materials at any time, ensuring that the learning process continues well beyond the official completion of the project's activities.
- *Centralization of best practices.* Digital tools facilitate the gathering and organization of *best practices* regarding plastic in a circular and climate-neutral economy. This digital hub allows for rapid updates and information sharing among partners in *Romania, Slovenia, Spain, and Italy,* avoiding the ecological costs associated with physical transportation or printed materials.
- *Establishing long-term impact.* A central objective is to use these digital results to *establish the long-term sustainability* of the EDU4-

PlastiCircular initiative. The digital infrastructure serves as a foundation for future research and continuous public education aimed at preventing plastic waste from entering the environment.

In summary, digitalization transforms education from a one-time event into a continuous and scalable process, which is essential for the transition to a climate-neutral economy.

EDU4PlastiCircular Training and Certification Framework

Project Overview and Objectives

The EDU4PlastiCircular project represents a pioneering Erasmus+-funded initiative specifically designed to address education for responsible practices in plastic circularity and microplastics awareness within higher education. The project aims to foster green skills through comprehensive training on interconnected topics including the plastic world, waste management, circular economy, innovation, and responsible environmental behaviour. As an international collaboration involving multiple European partner institutions, EDU4PlastiCircular exemplifies the transnational approach increasingly recognized as essential for addressing global environmental challenges.

The project's core objectives centre on developing educational capacity to prevent plastic waste from entering the environment while promoting circular economy principles. This dual focus on prevention and circularity distinguishes EDU4PlastiCircular from initiatives that address only waste management or recycling in isolation. The project explicitly recognizes that achieving a circular and climate-neutral plastic economy requires fundamental changes in how plastics are designed, produced, used, and managed at end-of-life.



More innovative ideas on how to exploit the EDU4PlastiCircular created resources and more about the project could be found on the project web page https://microplastics.today

According to the project proposal, the EDU4PlastiCircular project, developed under the Erasmus+ Programme, contributes to one or more of the following programme's policy priorities:HORIZONTAL – Environment and fight against climate change. Additionally, there has been select one more priority: HE – Supporting digital and green capabilities



FIGURE 2.3 Project Home page, https://microplastics.today/

of the higher education sector. The project addresses these priorities (Figure 2.4) in the following ways:

1. The project contributes towards a better understanding of the circular economy of plastics via an extended training programme. It provides learners (HEIS teachers/trainers, students and managers from companies) a European overview of the Plastics World including production, conversion into parts and products, consumption, waste collection and treatment, including recycling (end-of-life aspects as production of recycled plastics and re-use in different application sectors). Awareness and responsibility of trainers and trainees are key behaviour effects of EDU4PlastiCircular training. Innovative aspect: EDU4PlastiCircular project results define green capabilities for HEIS education and for other organizations, too.
2. It includes the use of digital technologies for EDU4PlastiCircular training/education programme and management (cloud-based collaboration tools for communication, document, project, versions, meetings, risks, issues, change management). Innovative aspect: those well-established approaches/methodologies of plastic in the circular and climate neutral economy will be transferred and adapted to different educational domains of HEIS partners (teaching, managing, other remote work).
3. It includes innovative pedagogies for EDU4PlastiCircular education, awareness and behavioural adaptation using virtual learning and collaboration (e.g., cyberpedagogy, blended learning, micro-



FIGURE 2.4 The Three Main Domains Addressed by EDU4 PlastiCircular Project
NOTES Created using ChatGPT.

learning units, peer learning, gestalt-pedagogy based group sessions which include learning with artistic expression, body expression, psychodrama and emotion expression).

4. It addresses the differences in relation to the access to meaningful work based on geography – online/remote education/teaching offers trainers/HEIS educators an equal opportunity for teaching jobs without the need for relocation.

Pedagogical Approach and Methodology

EDU4 PlastiCircular employs innovative pedagogies including virtual learning, cyberpedagogy, and hybrid educational formats to maximize accessibility and engagement. This multi-modal approach reflects contemporary understanding that effective sustainability education must accommodate diverse learning preferences and contexts. A comprehensive gap analysis conducted within the project assessed both current knowledge levels and perceived usefulness of circular economy and plastics topics among students and academic staff, providing an evidence base for curriculum development.

Research findings from the project indicate that hybrid learning was

the overall preferred format, with students showing a slight preference for face-to-face instruction, while online learning was the least popular option. PowerPoint presentations were identified as the most preferred learning material, while printed and digital books received lower preference ratings. These insights have direct implications for designing educational programs that align with learner needs and preferences, potentially enhancing engagement and learning outcomes.

The project's methodology emphasizes competence-based learning, focusing on developing practical skills alongside theoretical knowledge. This approach aligns with broader trends in sustainability education toward action-oriented learning that prepares students to address real-world challenges. The integration of topics spanning from fundamental chemistry and materials science to policy and behavioural change reflects the inherently interdisciplinary nature of circular economy challenges.



More details regarding the pedagogical approach designed for training circular economy principles and plastic circularity aspects in the context of the EDU4 PlastiCircular project could be find in (Figure 2.5): https://microplastics.today/project-results/ The most useful material is the handbook for trainers with innovative methods and ideas for the educational process (Figure 2.6).

The pedagogical resources of the EDU4 PlastiCircular project are designed with a sophisticated modular approach that aligns with European competency frameworks. The project moves beyond simple 'awareness' to provide a structured educational journey tailored for higher education and professional development. The discussion below outlines the primary pedagogical pillars of the project:

1. *Competency-based framework (the skill card).* The backbone of the project's pedagogy is a visual *Skill Card* (a tree-shaped representation of competencies). It aligns the training program with:
   - *GreenComp,* the European sustainability competence framework, focusing on critical thinking and personal agency in environmental protection.
   - *EQF (European Qualifications Framework),* the resources are designed to fit different educational levels, ensuring that a BSC student and a corporate manager both receive content at an appropriate depth.
2. *Tiered learning paths.* Unlike 'one-size-fits-all' courses, EDU4 Plasti-

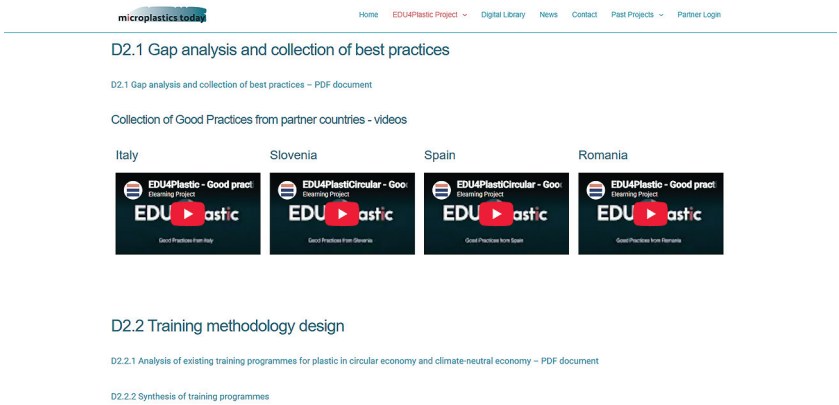


FIGURE 2.5 Access the D2.2 EDU4PlastiCircular Training Methodology Design



FIGURE 2.6 Handbook with Innovative Methods for Trainers

Circular utilizes *differentiated learning paths* (Level 1 to Level 3) to cater to three distinct target groups:

- *Students.* Focusing on technical knowledge and future-ready engineering skills.
- *Trainers/Educators.* Providing the methodological tools (the 'how-to') to transfer this knowledge to others.
- *Employees/Managers.* Emphasizing practical, implementation-ready solutions for making organizational processes 'greener.'

3. *Bloom's Taxonomy integration.* The curriculum is mapped using

Bloom's Taxonomy, ensuring a progression from basic knowledge and skills under the 'Remembering' level (understanding what microplastics are) to high-level skills 'Creating' (designing new circular economy solutions):

- *Foundation.* Terminology guides and 'About Plastics' readings.
- *Application.* Best practice case studies and cleaner production initiatives.
- *Evaluation.* Advanced sorting technologies and legislative compliance modules.

4. *Diverse teaching methods.* The instructional design is strongly aligned with modern sustainability framework, proposing a complex, modular learning environment, based on experiential, transformative, system-thinking paradigms:
   - *Dominant teaching & learning methods.* Expository methods (lectures and interactive lectures); Experiential learning (labs, simulations, workshops, internships); Inquiry-based learning (experiments, investigations); Problem-based learning (case studies, solution design) Project-based learning (prototyping, 3D printing); Gamification (quizzes, competitions); Reflective learning (diaries, vision maps, infographics, reflections); Collaborative learning (group work, role-play, debates).
   - *Competence orientation,* aligned with GreenComp framework. Systems thinking (e.g., plastic pathways, LCA); Critical thinking (evaluation of materials, policies); Action competence (solution design, sustainability audits); Self-awareness (reflection activities)
   - *Instructional architecture.* Each module is structured on topics comprising learning activities and assessment (LAAS) which integrate teaching methods for Lecture (knowledge input), Activity (active engagement); Assessment (feedback and validation), and Learning Resources.

5. *Diverse resource formats.* To accommodate different learning styles (visual, auditory, and kinesthetic), the pedagogical toolkit incorporates the following elements:
   - *Digital Library.* An open-access repository of e-books, multimedia presentations, and research papers.
   - *Interactive e-course.* Hosted on the Elearningproject.eu platform, featuring self-paced lessons and progress quizzes.

TABLE 2.1 Summary Table of Pedagogic Strategy

Feature	Pedagogic goal
Multilingual content	Inclusive access for diverse European populations.
Open Educational Resources (OER)	Promoting lifelong learning and accessibility.
Case study method	Bridge-building between theoretical knowledge and industry reality.
Continuous updates	Ensuring learners are informed by current scientific research (e.g., microplastics in the air/Antarctica).

- *Practical templates.* Worksheets that allow learners to audit plastic use in their own environments.

6. *Feedback and self-assessment.* A critical pedagogical feature is the *iterative assessment model.* The project uses a 'See What You Know' pre-assessment to baseline the learner's knowledge, followed by quizzes at the end of each module to validate progress. This allows for immediate reflection-a key principle of adult learning (*andragogy*).

By combining theoretical rigor with practical industry best practices, the EDU4 PlastiCircular project provides a robust ecosystem for anyone looking to transition from a 'linear' mindset to a 'circular' one.

Outcomes and Contributions

The EDU4 PlastiCircular project has generated valuable insights for designing educational programs aligned with the needs and preferences of students and academic staff in the circular economy and plastics domain. By conducting systematic gap analysis and preference assessment, the project provides an evidence-based foundation for curriculum development that can inform similar initiatives across different institutional contexts. The project's emphasis on green skills development addresses a critical need identified by the European Union and other policy bodies for workforce capacity in circular economy.

The project contributes to addressing the broader challenge of integrating sustainability into higher education curricula, which has been identified as essential for achieving Sustainable Development Goals. By focusing specifically on plastics and circular economy, EDU4 PlastiCircular provides a model for topic-specific sustainability education that

can complement broader environmental education initiatives. The project's international collaboration structure facilitates knowledge exchange and capacity building across European institutions, potentially accelerating adoption of circular economy education.

EDU4 PlastiCircular Digital Environment Development

The project Consotium has produced a range of deliverables, focusing on gap analysis, training methodology design, and open educational resources to define the training and certification programme. The most important EDU4 PlastiCircular project outcomes, defining *the created digital environment* that are visible and accessible for any learner are (Figure 2.7):

- Project webpage: https://microplastics.today/;
- Project deliverables, https://microplastics.today/project-results/;
- Digital library, https://microplastics.today/digital-library/;
- E-learning platform, https://elearningproject.eu/courses/edu4plasticircular-educating-for-sustainable-plastic-use-and-circular-economy/;

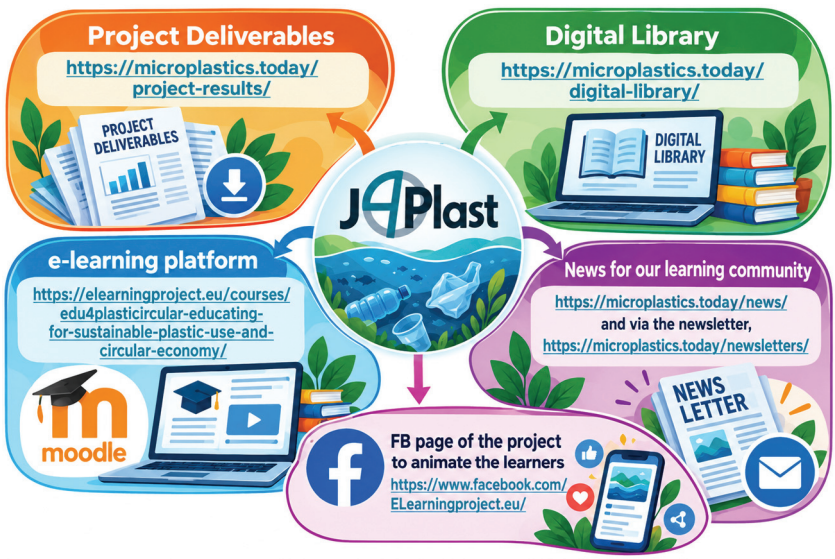


FIGURE 2.7 The Components of the EDU4 PlastiCircular Digital Environment (Created Using ChatGPT)

- News for our learning community: https://microplastics.today/news/ and via the newsletter, https://microplastics.today/newsletters/;
- FB page of the project to animate the learners https://www.facebook.com/Elearningproject.eu/.



Project web page, https://microplastics.today/

Microplastics.today is the official website for the EDU4PlastiCircular project, an Erasmus+ initiative funded by the European Commission. The site serves as an educational hub focused on the circular economy and the prevention of plastic waste and microplastics in the environment. Its primary features include:

- *Educational resources.* It hosts an E-course and a digital library containing materials related to plastic waste management and climate neutrality. This is the most populated area of the web dedicated to project deliverables, https://microplastics.today/project-results/ and the Digital Library, https://microplastics.today/digital-library/, too.
- *Project information.* It outlines the goals of the EDU4PlastiCircular project, which aims to provide education on preventing plastic pollution.
- *Collaborative network.* The site represents a partnership between several European institutions, including Universitatea Politehnica Timişoara (Romania), Universitat Politècnica de València (Spain), and the University of Insubria (Italy), among others.
- *Past initiatives.* It also maintains archives for previous related projects, such as the MicPlaPROB project.

The platform is available in multiple languages, including English, Italian, Romanian, Slovenian, and Spanish.

The library exhibits several key characteristics, outlined below:

1. *Content and formats.* The library contains a variety of educational and professional resources, including:

Digital Library, https://microplastics.today/digital-library/ is an open-access repository designed to support the EDU4 PlastiCircular project's mission of promoting a circular economy and sustainable plastic management.

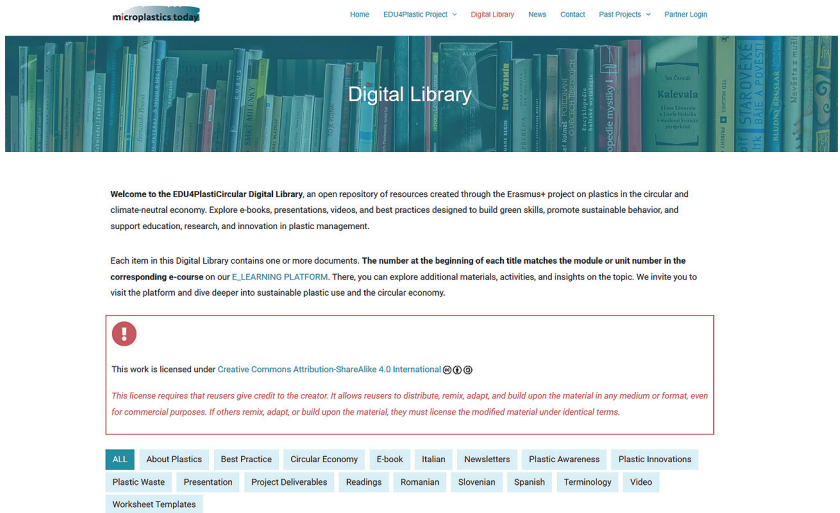


FIGURE 2.8 EDU4 PlastiCircular Digital Library

- *Presentations.* Visual slides covering specific modules.
- *Readings.* Detailed textual materials for deeper study.
- *Terminology guides.* Glossaries to help users understand technical language related to plastics and environmental science.
- *Worksheet templates.* Practical tools for educators and learners to apply the concepts.
- *Multimedia.* The repository also lists e-books, videos, and newsletters.

2. *Organizational structure.* The materials are organized to align directly with the project's *e-Learning Platform.* Each item is numbered (e.g., '1.1,' '1.2') to correspond with specific modules and units in the project's online courses.
   - Module 1.1: Focuses on plastics in daily life (uses, types, and impacts).
   - Module 1.2: Covers plastic materials typology and manufacturing technologies.

Subsequent modules explore recycling processes, environmental impacts, and circular economy strategies in greater depth.

3. *Multilingual support.* Reflecting the project's European partnership, the library provides translations for most documents. Resources are typically available in: English, Italian, Romanian, Slovenian, Spanish.
4. *Target topics.* Users can filter the library by various categories, such as:
   - *Circular economy.* Strategies for reducing waste and keeping materials in use.
   - *Plastic awareness.* Educating the public on environmental impacts.
   - *Best practices.* Real-world examples of successful plastic management.
   - *innovations.* New technologies and methods in the plastic industry.

The library is intended as a permanent resource for building 'green skills and competencies' among students, researchers, and professionals involved in environmental protection.



The e-learning platform, https://elearningproject.eu/courses/edu4plasticircular-educating-for-sustainable-plastic-use-and-circular-economy/

The created e-learning platform for implementing Massive Open Online Courses (MOOC) has been created (under the Moodle application) to host online courses and the Open Educational Resources (OERS) created and produced within the EDU4PlastiCircular Erasmus+ projects. All materials available on this platform are considered OERS, ready to be used and transferred into the higher education practices (for different courses, specialisations, programmes etc. and with different groups of students or learners). The e-learning platform is regularly updated by the EDU4PlastiCircular consortium members.

For most courses, registration is not required; however, *it is necessary to register* to participate in course forums, earn certificates of attendance, or receive Canvas Open Badges. The latter can be earned in some courses (Figure 2.9).

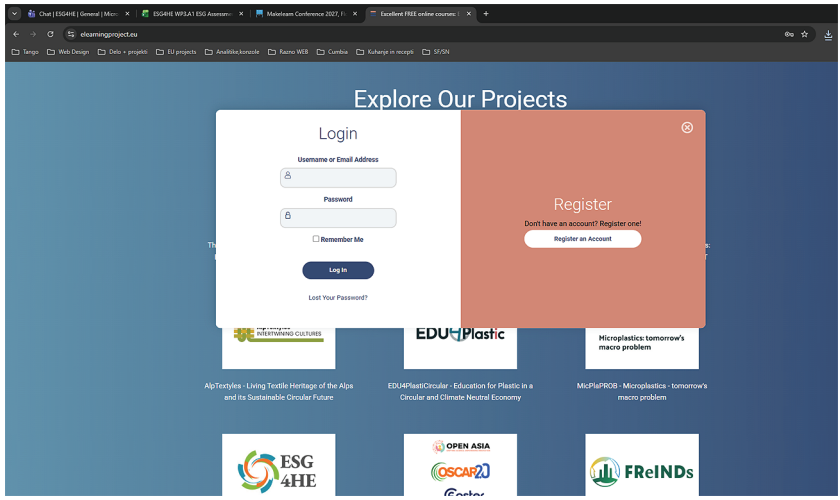


FIGURE 2.9 The Login and Register Page



BEFORE starting https://surveys.elearningproject.eu/microplastics-solving-expert/

AFTER completing the training and certification program, https://surveys.elearningproject.eu/microplastics-solving-expert/

FIGURE 2.10 'See What You Know' Survey to Gauge Knowledge Before and After the Course

Before starting the learning journey, it is recommended to check the actual knowledge of the potential learner and to offer a panorama of the knowledge considered in the EDU4PlastiCircular training program by having a preliminary assessment, using an online questionnaire. The same questionnaire is used after completion of the training to measure the degree of knowledge you achieve and to identify the areas of potential improvements.

The EDU4PlastiCircular e-course, titled 'Educating for Sustainable Plastic Use and Circular Economy.' This course is an Open Educational Resource (OER) developed under the Erasmus+ program to promote 'green skills' and responsible behaviour regarding plastic waste.



FIGURE 2.11 Description of the EDU4 PlastiCircular Training and Certification Programme per Modules

NOTES Structure of the E-Learning Platform and the Digital Library, created using ChatGPT.

1. *Core Modules.* The course is structured into five comprehensive modules, each containing several topics and quizzes (Figure 2.11 and Figure 2.12).
2. *Target audience.* The course is designed for adult lifelong learners (ages 18–65), specifically:
   - *Managers and employees.* To help green their organizational processes.
   - *HEI educators.* To transfer knowledge to students.
   - *Students (BSC, MSC, PhD).* Specifically, those in economics, management and engineering programs.
3. *Key features* of the e-learning platform are:
   - *Self-assessment.* Includes a 'See What You Know' survey to gauge knowledge before and after the course (Figure 2.10).
   - *Certification.* While registration isn't required to view materials, users must register to participate in forums and earn a Certificate of Attendance or Canvas Open Badges (Figure 2.13).
   - *Open Access.* All materials are provided under a Creative Commons license (BY-NC 4.0).



FIGURE 2.12 The Structure of the EDU4 PlastiCircular Training and Certification Programme

NOTES Created using ChatGPT.

- *Practical Tools.* Includes 'Smart Study Tips' and downloadable instructions for navigating the course and 'Instructions for Studying the Course' (Figure 2.13).

The overall goal is to shift the perspective of plastic from being seen merely as a pollutant to being treated as a valuable material that can be managed through smart, sustainable, and climate-neutral practices.

The News and Newsletter sections of the Microplastics.today platform serve as the primary communication channels for the EDU4 PlastiCircular learning community. They bridge the gap between academic research and everyday environmental awareness.



FIGURE 2.13 Procedure for the Recognition of Competencies upon Completion of an Online Course of EDU 4 PlastiCircular

News for our learning community:
Via the news page https://microplastics.today/news/

Via the newsletter, https://microplastics.today/newsletters/

1. *The News Section (Latest Updates).* The news feed provides real-time updates on project milestones, international outreach, and scientific insights (Figure 2.14). Key themes include:
   - *Global dissemination.* Recent articles highlight the project's expansion beyond Europe, such as presentations at the University of Eswatini and collaborations with the National University of Mongolia.
   - *Scientific awareness.* The feed features educational articles on 'hidden' plastic sources, such as microplastics in the kitchen or the discovery of plastic particles in remote areas like Antarctica.
   - *Academic collaboration.* It tracks meetings between partner universities (e.g., UPV in Spain, University of Insubria in Italy, and UPT in Romania) and Phd defenses that integrate project research.
   - *Communitye Events.* Reports on career fairs and youth aware-

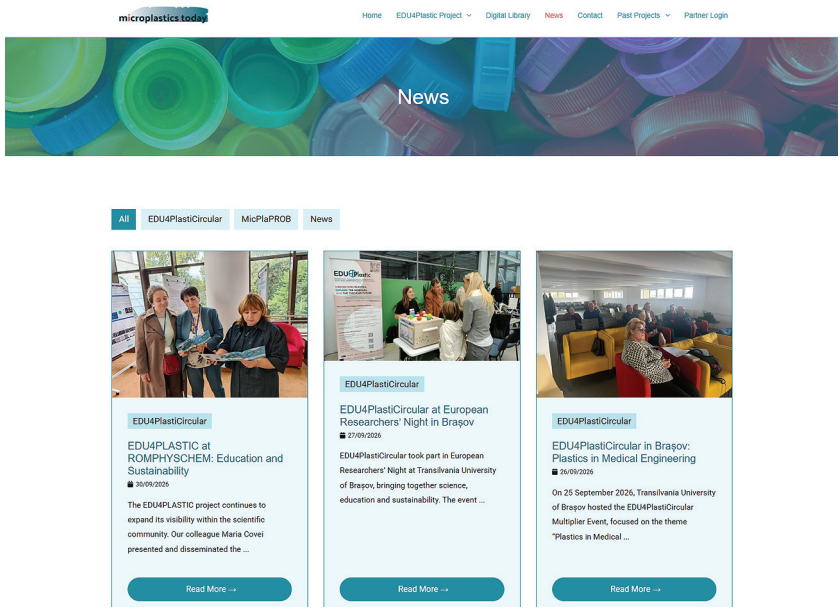


FIGURE 2.14 The News Section of the EDU4PlastiCircular Web Page (https://microplastics.today/news/)

ness programs (like 'Plastic Matters') where the project helps promote environmental careers.

2. *The newsletters (Project Milestones).* The newsletters serve as a formal record of the project's progress, typically released every few months (Figure 2.15). They are designed to:
   - *Synthesize results.* Each edition compiles the most important research findings and educational tools developed during that period.
   - *Announce resources.* They notify the community about new additions to the Digital Library, such as Spanish-language e-books or updated e-learning modules.
   - *Engage partners.* They spotlight the activities of specific partner institutions, ensuring that all stakeholders (students, teachers, and managers) are aligned with the project's circular economy goals.

Together, these channels ensure the learning community stays informed about the *lifecycle of plastic* – from the laboratory and class-

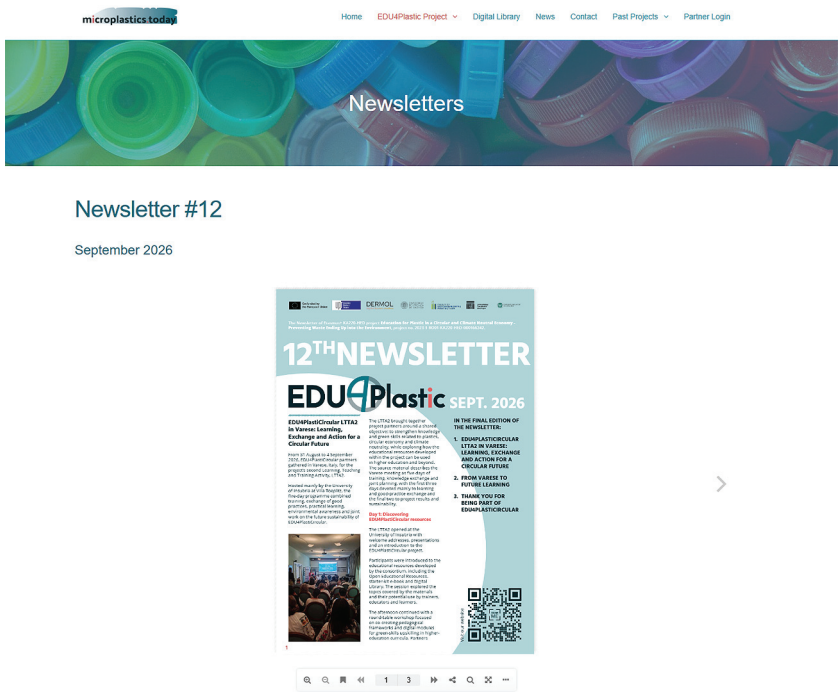


FIGURE 2.15 The Web Page of the EDU4PlastiCircular Newsletters (https://microplastics.today/newsletters/)

room to policy changes and individual consumer habits. For learners, following these updates is essential for staying current with the evolving standards and innovations in the circular economy.

FB page of the project to animate the learners
https://www.facebook.com/Elearningproject.eu/

The Facebook page for the Elearningproject.eu (which hosts the EDU4PlastiCircular project) acts as a dynamic social extension of the learning platform, specifically designed to *animate and engage learners* through interactive and visual content. Key features of the page that support the EDU4PlastiCircular community include (Figure 2.16):

1. *Interactive contests and student engagement.* The page is used to

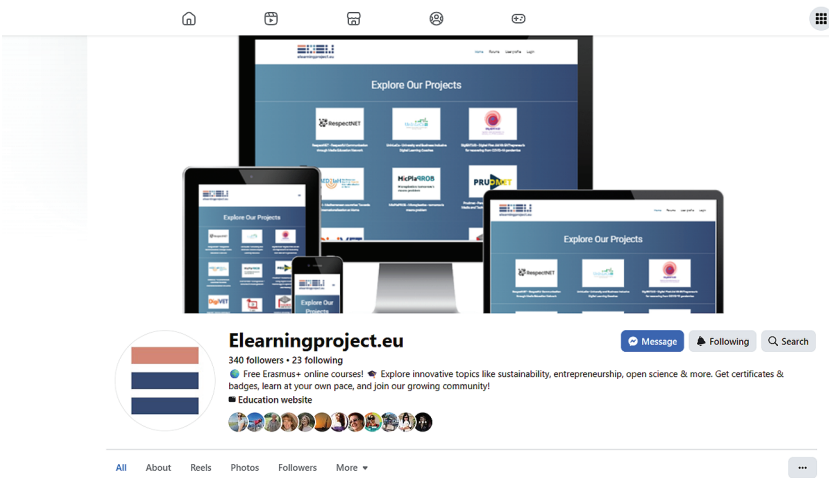


FIGURE 2.16 The Facebook Page That Hosts the EDU4 PlastiCircular Project Community

run awareness-raising activities that involve direct participation. A notable example is the 'Prevent Waste, Protect Our Planet' Facebook Contest, where students (such as those from the Transilvania University of Brasov, Romania) created social media announcements to educate the public about plastic pollution. This gamifies the learning process and encourages students to apply their 'green skills' in a real-world digital marketing context.

2. *Dissemination of results and news.* The page serves as a 'live' bulletin board for the project, sharing:
   - *Event highlights.* Photos and updates from international conferences (like MakeLearn or the Symposium on Circular Economy) and workshops where the project's results are presented.
   - *Newsletter alerts.* Announcements of new newsletter releases (e.g., the 8th edition), ensuring learners do not miss key project milestones.
   - *Collaboration news.* Updates on meetings between European partners, showing the international scale of the initiative.
3. *Educational 'bites' and awareness.* To keep learners motivated between formal modules, the page shares bite-sized insights, such as:
   - Facts about *microplastics in everyday environments* (like kitchens or remote regions).

- Tips for *sustainable habits,* such as waste-free meal preparation and plastic-free to-go meals.
- Discussions on *policy and legislation,* making complex topics more accessible through social media posts.

4. *Community building.* By following the page, learners become part of a larger European network. It facilitates:
   - *Networking.* Connecting students, HEI teachers, and managers across different countries (Italy, Slovenia, Romania, Spain, etc.).
   - *Open discussion.* Providing a space for feedback and debate on practical plastic waste management experiences.

In summary, while the e-learning platform provides the formal structure, the Facebook page provides the 'pulse' of the project, transforming educational content into a social dialogue that keeps learners motivated and connected to the environmental cause.

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Chapter Three

Actual Challenges of Plastic Waste Prevention and Management

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https://doi.org/10.53615/978-83-65020-56-7/67-145

The growing accumulation of plastic waste represents a complex and multidimensional challenge that intersects environmental, technological, economic, and societal domains. Despite increased awareness and policy initiatives, global plastic production and consumption continue to rise, while recycling and recovery systems remain insufficiently developed to cope with the scale of waste generated (Davis, 2022; Islam, 2025). Plastic waste management is further complicated by the persistence of plastics in natural environments, their fragmentation into micro- and nanoplastics, and the limited efficiency of current recycling technologies. These challenges highlight the need for systemic solutions that integrate technological innovation, material redesign, and behavioural change.

This chapter explores three interconnected dimensions of plastic waste prevention and management: (1) the scientific challenges and environmental and health impacts of micro- and nanoplastics, (2) emerging material innovations and engineering approaches, and (3) future-oriented visions for sustainable plastic management within a circular economy framework.

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Understanding the Impact of Micro- and Nanoplastics in Modern Environmental Science and Education

The proliferation of plastic materials in modern society has led to the pervasive presence of microplastics (MPS) and nanoplastics (NPS) across all environmental compartments, including the atmosphere, hydrosphere, and lithosphere. As emerging global pollutants, these particles pose significant ecological and health risks that are not yet fully understood. This brief overview examines the current challenges in micro/nanoplastics (MNP) research, scientific evidence on MNP environmental and health impacts, and the contributions of the EDU4 PlastiCircular project as an educational and circular economy response to these challenges.

Current Challenges in Micro/Nanoplastics Research

One of the primary challenges in the field of MNP research is the technical difficulty associated with the detection, identification, and quantification of these particles, particularly those at the nanoscale. While analytical technologies have improved for micro-sized fragments, characterizing particles smaller than 1 micrometer remains complex due to their interactions with environmental matrices and the lack of standardized protocols (Kochanek et al., 2025). This lack of harmonization continues to hinder comparability across studies and complicates risk assessment.

Furthermore, the continuous fragmentation of macroplastics into smaller MNPS ensures a persistent source of pollution that is difficult to mitigate once released into the environment (Izuafa et al., 2026). Environmental concentrations are highly heterogeneous, influenced by particle characteristics, environmental conditions, and co occurring stressors, which makes modelling long term fate and transport particularly challenging.

Recent studies have highlighted the atmospheric transport of MNPS as a significant pathway for global contamination. Research indicates that urban atmospheres contain substantial concentrations of these particles, which can be inhaled by humans and deposited in remote ecosystems (Hu et al., 2026). However, robust long term exposure data remain scarce, especially for nanoplastics, which are often under detected due to methodological constraints. The health implications of such exposure are a growing concern, with evidence suggesting potential links to cancer, cardiovascular diseases, and reproductive is-

TABLE 3.1 A Synthesis of the Key Challenges in MNP Research

Research area	Key challenges	Significant findings
Detection and analysis	Lack of standardized sampling and extraction protocols for nanoplastics.	Improved Py-GC/MS methods for identification of unknown microplastics.
Environmental fate	Understanding the fragmentation rates and long-term persistence in soil and water.	MNPS are now found in all major environmental compartments globally.
Health impacts	Scarcity of robust human exposure data and long-term epidemiological studies.	Potential links to inflammation, oxidative stress, and reproductive toxicity.

sues (Gladwell et al., 2026). Yet, epidemiological studies remain limited.

A more detailed discussion of these scientific and methodological limitations, including their implications for research design and data interpretation, is presented within the following section and the subsection Key Challenges and Research Priorities.

Impacts of Micro- and Nanoplastics in the Modern Environment

Microplastics (MPS, <5 mm) and nanoplastics (NPS, <1 μm) have become a defining environmental challenge of the 21st century. Their persistence, mobility, and capacity to interact with chemical and biological systems position them as pollutants of global concern (Jiang et al., 2020; Winiarska et al., 2024; Zhang et al., 2019). MPS originate from both primary sources, such as industrial pellets, microbeads, textile fibres, and secondary sources, which include fragmentation of larger plastic items through UV exposure, mechanical abrasion, and environmental weathering (Borriello et al., 2023; Gunawardhana et al., 2023; Kasmuri et al., 2022). Because they are resistant to degradation, MPS and NPS accumulate across environmental compartments and increasingly influence ecological processes and human exposure pathways.

Although public perception often frames microplastic pollution primarily as a marine issue, scientific evidence shows that most microplastics originate on land and later reach the oceans through rivers, stormwater, wastewater, and atmospheric deposition (Boucher & Friot, 2017; Lambert & Wagner, 2017; Sunny et al., 2025). Around 70% of all microplastic emissions originate from land-based sources, including urban runoff, wastewater, tire wear, synthetic textiles, and mismanaged

waste (Lambert & Wagner, 2017; Sonke et al., 2025; Sunny et al., 2025). Once in the marine environment, however, microplastics accumulate extensively and persist for decades, making the ocean the final sink for a large share of global plastic pollution.

The majority of marine microplastics (up to 85%) originate from the degradation of larger plastic items, confirming that secondary microplastics dominate the global oceanic burden (Eriksen et al., 2023). Primary microplastics represent only a fraction of the total microplastic burden in the marine environment. Global assessments estimate that 15–31% of microplastics entering the oceans originate from primary sources. Among primary sources, synthetic textile fibres released during washing and wearing account for approximately 35% of emissions, followed by tire and road-wear particles (28%), city dust including paints and coatings (24%), marine coatings (3.7%), microbeads in personal care products (2%), and industrial pellet loses (1%) (Boucher & Friot, 2017; Kershaw, 2015; Kershaw & Rochman, 2015; Lambert & Wagner, 2017).

Global Distribution and Environmental Presence

MPS and NPS are now documented in marine, freshwater, terrestrial, and atmospheric systems, including some of the most remote regions on Earth, such as deep-sea trenches (Lebreton et al., 2018), glaciers (Zhang et al., 2021), and Arctic ice (Wheatley, 2024). Marine sediments act as long-term sinks, with hotspots such as fjords reaching ~7,000 particles/kg dry sediment, while subtropical gyres accumulate extremely high loads (~1,000,000 particles/km^2) (Vázquez & Rahman, 2021; Wheatley, 2024).

Recent global modelling estimates indicate that the world's oceans currently contain approximately 170 trillion microplastic particles, corresponding to about 2.3 million tonnes of material. Subtropical gyres remain the most contaminated regions, with the North Pacific subtropical gyre showing the highest accumulation of floating microplastics worldwide (Eriksen et al., 2023).

Freshwater systems show similarly widespread contamination, with rivers such as the Rhine reporting surface-water concentrations near 900,000 particles/km^2 and lakes such as Lake Garda showing up to ~1,108 particles/m^2 in shoreline sediments (Imhof et al., 2013). Rivers are the dominant transport pathway of land-based plastics to the ocean, with ~1,000 rivers responsible for nearly 80% of global riverine



FIGURE 3.1 Plastic Waste Along Water Bodies as a Key Source of MNP Contamination (FVO)

plastic emissions (Lebreton et al., 2017). Freshwater contamination is further exacerbated by wastewater treatment plants (WWTPS), which can discharge millions of MP particles per day when overloaded or lacking advanced filtration (Hechmi et al., 2024). Even when removal efficiency is high, most captured MPS accumulate in sewage sludge, which is frequently applied to agricultural soils and therefore represents a major secondary pathway for environmental exposure. Sludge is widely recognized as the primary sink for MPS within WWTPS, and its agricultural application is consistently associated with elevated MP concentrations in croplands, with potential implications for soil structure, fertility, and biota (Hooge et al., 2023).

Beyond sludge, agricultural soils receive MPS from multiple additional sources, including pesticide and fertilizer additives, organic waste and compost, mulch films, wastewater irrigation, and atmospheric deposition. Atmospheric transport redistributes MPS globally, with deposition documented in mountain regions, polar snow, and urban air (Allen et al., 2019; Zhang et al., 2020), confirming that airborne pathways can move plastics across continents and reintroduce them into both aquatic and terrestrial systems (Evangeliou et al., 2020). Together, these inputs contribute to long-term accumulation in terrestrial environments. The mobility and long-term fate of MPS in soils depend strongly on particle characteristics, soil physicochemical properties, farming practices, and the heterogeneity of soil biota, all of which influence how MPS are transported, retained, or transformed within terrestrial ecosystems (Hooge et al., 2023; Uwamungu et al., 2022).

Environmental and Ecological Impacts

In aquatic environments, ingestion by plankton, invertebrates, fish, and seabirds is widely documented (Jiang et al., 2020; Sunny et al., 2025). A recent study reported that MPS have been found in 73% of fish species sampled in the North Atlantic, indicating pervasive food-web exposure (Lourenço et al., 2025).

Beyond the physical impacts of ingestion, MPS can also exert toxicological effects on marine organisms. Their hydrophobic surfaces readily adsorb and concentrate contaminants such as persistent organic pollutants (POPS), heavy metals, bisphenol A (BPA), phthalates, and polychlorinated biphenyls (PCBS). Once ingested, these chemicals may desorb into tissues, contributing to physiological stress, endocrine disruption, reproductive impairment, and increased mortality in exposed organisms (Grattagliano et al., 2025; Ojha, 2022; Sunny et al., 2025; Wheatley, 2024). In this sense, MPS function as vectors for chemical contaminants. However, emerging evidence shows that they also act as carriers of biological hazards. Biofilms forming on MP surfaces, so-called 'plastisphere,' can harbour pathogens and antibiotic-resistant bacteria, raising concerns about combined chemical and biological risks within aquatic ecosystems (Jia et al., 2024; Verma & Prakash, 2022).

MPS and NPS influence terrestrial ecosystems through multiple pathways. At the microbial level, they can reduce microbial biomass, disrupt community composition, and alter soil structure (Boots et al., 2019; de Souza Machado et al., 2018). Beyond these microbiological impacts, MPS also affect a wide range of soil organisms. Earthworms, nematodes, springtails, and other invertebrates show reduced reproduction, impaired growth, and altered behaviour even at low concentrations, indicating high sensitivity of soil fauna (Liu et al., 2023). Plants are similarly vulnerable. MPS can induce oxidative stress, damage root tissues, hinder nutrient uptake, and suppress germination and biomass production (Jia et al., 2023).

Together, these findings show that MPS affect not only soil animals but also plants, microbes, and broader soil functioning, underscoring the complexity of terrestrial microplastic pollution.

Human Exposure and Health Considerations

Humans are described as being exposed primarily through ingestion and inhalation (and to a lesser extent dermal contact), with subsequent

deposition and distribution to multiple tissues (Domenech & Marcos, 2021; Moorthy et al., 2025; Rehman et al., 2025). MPS and NPS are increasingly measured in human blood and multiple tissues, including cardiovascular plaques, lungs, placenta, gastrointestinal specimens, and brain, indicating systemic internal exposure rather than purely environmental presence (Leslie et al., 2022; Nihart et al., 2025; Roslan et al., 2024; Tan et al., 2020; Zurub et al., 2024). Concern focuses on small particle size as a determinant of deposition and translocation, emphasizing that particles smaller than 10 μm can reach the lower lungs and that particles smaller than 2.5 μm can reach the alveoli and potentially enter the bloodstream (Wardana et al., 2025).

Quantitative human exposure estimates indicate that adults may ingest 39,000–52,000 MP particles per year (Kannan & Vimalkumar, 2021), while inhalation exposure in indoor environments may reach ~68,000 particles/day (Wardana et al., 2025). Polypropylene infant feeding bottles can release extremely high numbers of microplastics, up to 16.2 million particles per liter, indicating that infants worldwide may be exposed to far higher levels of microplastics during formula preparation than previously recognized (Li et al., 2020). Atmospheric deposition on food surfaces and inhalation of synthetic fibres from textiles contribute significantly to daily exposure (Ageel et al., 2022).

MPS are also present in parts of our daily diet, having been detected in seafood, salt, honey, sugar, milk, fruits, and meat from chickens, cows, and pigs. Additionally, MPS have been found in drinking water itself, further underscoring their presence across commonly consumed food and beverage items and indicating that these pathways cumulatively increase the total microplastic intake into the human body. Additionally, trophic transfer through seafood consumption is well documented and represents an additional dietary exposure route (Pironti et al., 2021).

Cellular uptake is size-dependent, with nanoplastics internalized via endocytosis and capable of crossing biological barriers, including the blood-brain barrier (Chulkov et al., 2025). MPS and NPS exert biological effects through particle-related, chemical, and vector mechanisms. Mechanistic pathways include oxidative stress, inflammation, mitochondrial dysfunction, genotoxicity, endocrine disruption, and barrier impairment across respiratory, cardiovascular, gastrointestinal, and reproductive systems (Hernández et al., 2025; Preda et al., 2024). Although long-term health effects remain under investigation, current

evidence suggests potential links to inflammation, oxidative stress, endocrine disruption, and respiratory impacts (Tran et al., 2026).

Key Challenges and Research Priorities

Despite rapid scientific progress, uncertainties remain in understanding the full extent of MPS and NPS impacts on environmental and human health. Pollution presents a series of complex challenges that hinder effective assessment and management. Understanding long-term ecological and human health impacts requires integrated, multi-species, and ecosystem-level research.

In natural systems, MPS and NPS interact with soils, sediments, water bodies, and biota, where they undergo fragmentation, aging, and chemical transformation. These processes alter particle mobility, toxicity, and bioavailability, yet remain insufficiently characterized. Environmental concentrations are highly heterogeneous across ecosystems, and interactions with co-occurring stressors, such as heavy metals, pesticides, and climate-driven changes, remain poorly understood. Addressing these uncertainties requires integrated, multi-species, and ecosystem-level research capable of capturing trophic transfer, cumulative exposure, and long-term ecological feedback.

A consistent limitation across studies is the lack of standardized sampling and analytical methods, which complicates cross-study comparisons and risk assessment (Wheatley, 2024). NPS pose an even greater challenge: due to their extremely small size and current methodological constraints, they are frequently under-detected, leading to systematic underestimation of the most bioavailable and potentially hazardous fractions (Caputo et al., 2021; Miloloža et al., 2021). In human health research, the lack of harmonized detection and quantification methods for MPS and NPS in human tissues restricts comparability between studies and limits epidemiological interpretation (Cunningham et al., 2023; Iovino et al., 2026; Yee et al., 2021). Toxicokinetic parameters, including residence time in blood, organ distribution, and excretion pathways, are also poorly understood (Ricci, 2024), making it difficult to establish exposure thresholds or predict long-term health outcomes. To clarify potential causal relationships between MP exposure and chronic disease, large, well-powered longitudinal studies are urgently needed (Tran et al., 2026).

Policy frameworks are evolving, including the United Nations Environment Assembly (UNEA) resolution to negotiate a legally binding

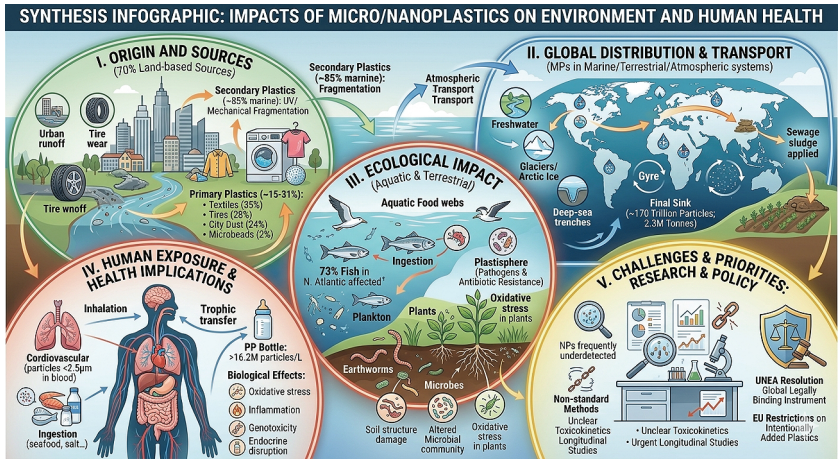


FIGURE 3.2 Micro/Nanoplastics Impacts and Challenges (Developed Using Gemini AI Application)

global instrument to end plastic pollution and EU restrictions on intentionally added microplastics (European Commission, 2023; Guo & Hu, 2025; UNEA, 2022). However, regulatory thresholds, environmental quality standards, and harmonized monitoring protocols remain largely absent. Establishing these tools will be essential for effective risk management, international comparability, and long-term environmental protection.

In conclusion, Table 3.2 (pp. 76–78) and Figure 3.6 (p. 80) present a synthesis of the aspects debated in this sub-chapter.

The EDU4PlastiCircular Project Contributions to Circular Economy

The EDU4PlastiCircular project addresses these challenges by focusing on education, awareness, and the implementation of circular economy principles. A central theme of the project is the prevention of plastic waste leakage into the environment through better management and innovative design.

Scientometric and Trend Analysis

Research associated with the EDU4PlastiCircular project has employed advanced scientometric tools to map the landscape of plastic-related health research. For instance, Repanovici et al. (2025) utilized VOSviewer to analyse the impact of plastic indoor materials on hu-

TABLE 3.2 Synthesis of Topics: Micro/Nanoplastics Impacts and Challenges

Major topics/specific sub-topics addressed	Supporting references
Introduction to the challenge	
Definition (MPS <5 mm, NPS <1 μm) as a defining challenge of the 21st century.	Winiarska et al. (2024)
Persistence, mobility, and capacity to interact globally.	Jiang et al. (2020); Winiarska et al. (2024); Zhang et al. (2019)
Origin and sources of plastics	
Land-based origins: ~70% from urban runoff, wastewater, tire wear, textiles, and waste.	Lambert & Wagner (2017); Sonke et al. (2025); Sunny et al. (2025)
Secondary plastics (fragmentation): Dominate marine burden (up to 85%), created via UV, mechanical abrasion, and weathering.	Borriello et al. (2023); Eriksen et al. (2023); Gunawardhana et al. (2023); Kasmuri et al. (2022)
Primary plastics (industrial/direct): 15–31% of marine entrance. Main sources: textiles (35%), tire wear (28%), city dust/paints (24%). Microbeads are 2%.	Boucher & Friot (2017); Eriksen et al. (2023); Kershaw (2015); Kershaw & Rochman (2015); Lambert & Wagner (2017)
Global distribution and transport	
Documented presence in deep-sea trenches, glaciers, and Arctic ice	Lebreton et al. (2018); Wheatley (2024); Zhang et al. (2021)
Oceans as the final sink, containing an estimated 170 trillion particles (2.3 million tonnes).	Eriksen et al. (2023); Vázquez & Rahman (2021)
Freshwater pathways: Rivers are the dominant transport route, with ~1,000 rivers carrying 80% of emissions.	Hechmi et al. (2024); Imhof et al. (2013); Lebreton et al. (2017)
Terrestrial sinks: Sewage sludge application in agriculture is a major secondary exposure pathway for croplands.	Hechmi et al. (2024); Hooge et al. (2023)
Atmospheric transport: Redistribution globally, moving plastics across continents and reintroducing them to aquatic/terrestrial systems.	Allen et al. (2019); Evangeliou et al. (2020); Zhang et al. (2020)

Continued on the next page

man health, identifying key thematic directions and research gaps. This analysis underscores the importance of indoor air quality and the role of microplastics generated from common household materials (Repanovici et al., 2025).

The scientometric analysis revealed a growing interest in the research, coming from different traditional study domains and indicates the importance of further research in this area. Key themes identified included sources of plastics indoors, chemicals responsible for envi-

TABLE 3.2 *Continued from the previous page*

Major topics/specific sub-topics addressed	Supporting references
Environmental and ecological impacts	
Aquatic: Ingestion documented across food webs (plankton to seabirds). 73% of North Atlantic fish species affected.	Jiang et al. (2020); Lourenço et al. (2025); Sunny et al. (2025)
Vectors of toxicity: Hydrophobic surfaces adsorb and concentrate POPS, heavy metals, BPA, and PCBS.	Grattagliano et al. (2025); Ojha (2022); Sunny et al. (2025); Wheatley (2024)
Biological hazards: The 'plastisphere' harbours pathogens and antibiotic-resistant bacteria.	J. Jia et al. (2024); Verma & Prakash (2022)
Terrestrial: Microplastics alter soil structure, reduce microbial biomass, and harm invertebrates (earthworms).	Boots et al. (2019); de Souza Machado et al. (2018); Liu et al. (2023)
Plants: Induction of oxidative stress, root damage, and suppressed germination.	Jia et al. (2023); Sunny et al. (2025)
Human exposure and health implications	
Primary pathways: Ingestion (major diet components: seafood, salt, honey, milk) and Inhalation.	Ageel et al. (2022); Domenech & Marcos (2021); Moorthy et al. (2025); Pironti et al. (2021); Rehman et al. (2025); Wardana et al. (2025)
Internal presence: Systems measurement in blood, cardiovascular plaques, lungs, placenta, gastrointestinal specimens, and brain.	Leslie et al. (2022); Nihart et al. (2025); Roslan et al. (2024); Tan et al. (2020); Zurub et al. (2024)
Size as determinant: Particles <2.5 μm can enter the bloodstream.	Chulkov et al. (2025); Wardana et al. (2025)
Specific exposure risks: Polypropylene feeding bottles release up to 16.2 million particles per liter. Trophic transfer through seafood.	Kannan & Vimalkumar (2021); Li et al. (2020); Pironti et al. (2021)
Biological/Mechanistic effects: Oxidative stress, inflammation, mitochondrial dysfunction, genotoxicity, endocrine disruption, and barrier impairment.	Hernández et al. (2025); Moorthy et al. (2025); Preda et al. (2024); Rehman et al. (2025); Tran et al. (2026); Winiarska et al. (2024)

Continued on the next page

ronmental contamination and consequently of human health problems (Repanovici et al., 2025).

In terms of waste management, studies within the project have analysed recycling trends across the European Union. Giurea et al. (2026) examined packaging waste recycling rates in Central and Eastern Europe, comparing them against the EU-27 reference path. According

TABLE 3.2 *Continued from the previous page*

Major topics/specific sub-topics addressed	Supporting references
Challenges and research priorities	
Knowledge gaps: Long-term ecological feedback, cumulative exposure, and the impact of NPS are poorly understood.	Cunningham et al. (2023); Domenech & Marcos (2021); Nihart et al. (2025); Roslan et al. (2024); Tran et al. (2026); Wheatley (2024); Yee et al. (2021)
Methodological constraints: Systematic lack of standardized sampling and analytical methods hampers cross-study comparisons.	Caputo et al. (2021); Cunningham et al. (2023); Iovino et al. (2026); Nihart et al. (2025); Roslan et al. (2024); Tran et al. (2026); Wheatley (2024); Yee et al. (2021)
Toxicokinetics: Poor understanding of residence time in organs and excretion pathways.	Ricci (2024); Tran et al. (2026)
Need for research: Urgency for large, well-powered longitudinal studies to clarify causal links to chronic disease.	Tran et al. (2026)
Policy and regulation	
Current state: Regulatory thresholds, environmental quality standards, and harmonized monitoring are largely absent.	Caputo et al. (2021); Guo & Hu (2025); Tran et al. (2026); Wheatley (2024); Yee et al. (2021)
Developing frameworks: UNEA resolution to negotiate a global legally binding instrument; EU restrictions on intentionally added plastics.	European Commission (2023); Guo & Hu (2025); Nihart et al. (2025); Roslan et al. (2024); Tran et al. (2026); UNEA (2022)

to their findings indicate that while some countries are converging toward higher recycling targets, others face significant challenges in meeting the requirements for a circular economy, which could lead to increased environmental leakage of plastics (Giurea et al., 2026).[1]

'The results indicate that the EU-27 recycling rate remains high and relatively stable (average 78.7%), albeit with a slight downward trend (−0.44%) across the analysed interval. Poland and Bulgaria record overall improvements relative to their initial levels, while Hungary, and particularly Romania, exhibit declining trends and persistent negative gaps compared to the EU-27 benchmark. Poland stands out by surpassing the EU-27 average after 2019, reporting exceptionally high recycling

[1] More details at https://www.mdpi.com/2313-4321/11/3/51



FIGURE 3.3

EU-27 Observed Series and Fitted Linear Trend (2014–2023).

NOTES Created using ChatGPT, based on Giurea et al. (2026)

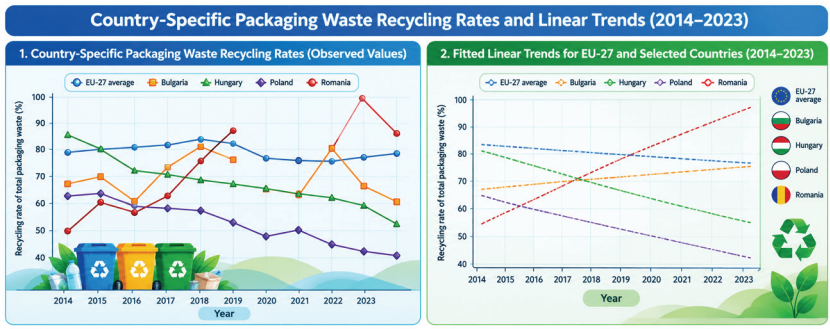


FIGURE 3.4 Country-Specific Observed Series

NOTES Created using ChatGPT, based on Giurea et al. (2026).

rates in several years, whereas Romania consistently records the largest deviation, with an average gap exceeding 20% in the later period. These findings reveal substantial heterogeneity in the implementation of EU packaging waste policies and highlight the need for targeted, country-specific interventions in Member States facing structural constraints in recycling capacity and collection systems' (Giurea et al., 2026).

Education and Green Skills

A core objective of EDU4PlastiCircular is the development of 'green skills' among students and professionals. By integrating innovative training methods (supported by MOOC) and the created Digital Library, the project aims to foster a deeper understanding of the plastic lifecycle and the environmental consequences of mismanagement (Draghici et al., 2024). The project is focused most on creating an innovative way for the *education of the circular economy approach* (Figure 3.5). This educational approach is vital for transitioning toward



FIGURE 3.5 The Circular Economy Approach

NOTES Addressed by EDU4 PlastiCircular Training Programme, created using ChatGPT.

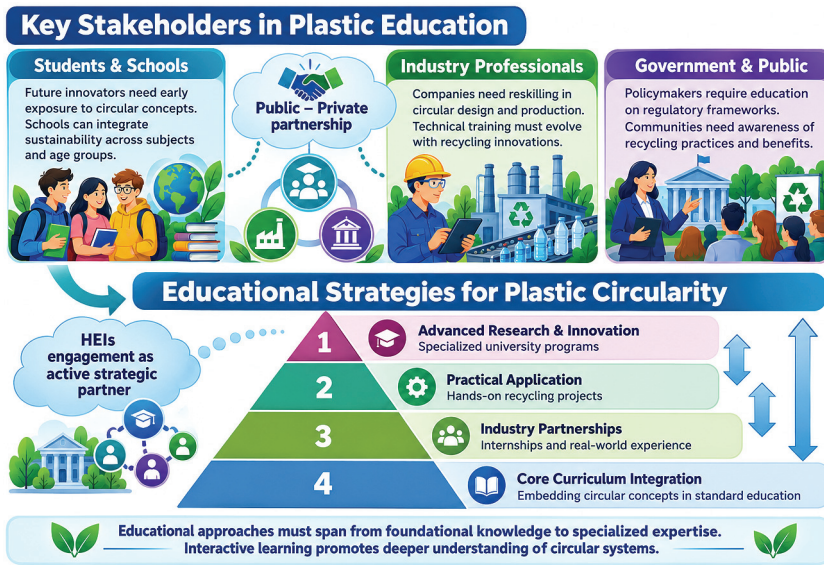


FIGURE 3.6 The Proposed Synthesis of the Education Approach for Plastic Circularity and Circular Economy

NOTES Created using ChatGPT.

a climate-neutral economy where plastic is treated as a valuable resource rather than waste. EDU4 PlastiCircular approach is presented in Figure 3.6 and Figure 3.7.

According to the Figures 3.5–3.7, *the proposed educational approach*

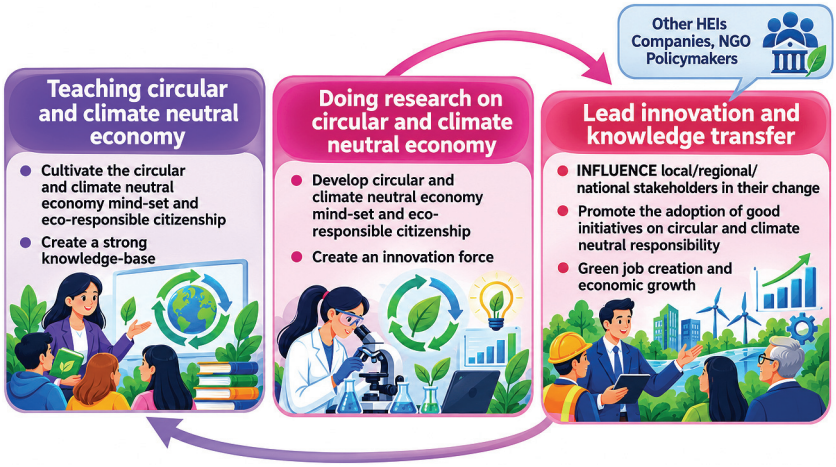


FIGURE 3.7 The Role of HEIS in Supporting the Real Transition to the Circular and Climate Neutral Economy

NOTES Created using ChatGPT.

combines specific resources provided by HEI with a strong alliance with diverse local stakeholders. This alliance, together with the created EDU4-PlastiCircular digital environment, will generate a powerful learning experience in the context offer by the Living Labs opportunities.

Living Labs are modern user-centric, open innovation ecosystems set in real-life environments which are adequate for education in the field of sustainability, circular and carbon neutral economy.[2] They integrate research and innovation processes, engaging citizens, companies, and government to co-create, test, and validate new technologies, services, or products in real time. These platforms focus on sustainable impact through iterative feedback.

According to the European Network of Living Labs:[3] 'Living Labs are open innovation ecosystems in real-life environments using iterative feedback processes throughout a lifecycle approach of an innovation to create sustainable impact. They focus on co-creation, rapid prototyping & testing and scaling-up innovations and businesses, providing (different types of) joint value to the stakeholders involved. In this context, living labs operate as intermediaries/orchestrators among citizens, research organizations, companies and government agen-

[2] More details at https://ec.europa.eu/newsroom/rtd/items/810822/en
[3] See https://enoll.org/about-us/

cies/levels. Within a wide variety of living labs, they all have common characteristics, but multiple different implementations. A Living Lab can be initiated and hosted in a university, city, research institute, municipality, or any space where the user is placed at the center of the co-creation process.'

Key characteristics and components of Living Labs are:

- *Real-life settings.* Testing happens in real environments (e.g., smart cities, neighborhoods) rather than controlled labs.
- *Co-creation.* Users are active participants in the innovation process, not just passive test subjects.
- *Multi-stakeholder collaboration.* Involves partnerships between users, researchers, public authorities, and companies.
- *Iterative processes.* Uses rapid prototyping and cyclical feedback to refine solutions.
- *Sustainability focus.* Many projects target environmental or societal challenges.

Commonly used methodologies for Living Labs are:

- Co-creation means involving stakeholders to generate ideas and design concepts.
- Exploration is related to identifying user needs and mapping the social context.
- Experimentation means testing products or services in real-world scenarios.
- Evaluation means assessing the impact and collecting user feedback on the innovation.

According to the European Network of Living Labs, these environments act as intermediaries between developers and users, facilitating faster development cycles. The European Commission has highlighted their role in creating practical solutions,[4] and according to Wikipedia,[5] they are often used in urban planning, health, and energy sectors which are excellent contexts to identify and discuss about plastic circularity, too.

In conclusion, understanding the impact of micro/nanoplastics in the modern environment requires a multidisciplinary approach that

[4] More details at https://ec.europa.eu/newsroom/rtd/items/810822/en
[5] More details at https://en.wikipedia.org/wiki/Living_lab

combines advanced analytical techniques with robust policy frameworks and educational initiatives. While technical challenges in particle detection and health risk assessment persist, projects like EDU4-PlastiCircular provide a necessary roadmap for mitigating these impacts through circular economy practices and public awareness. Continued research and international cooperation remain essential to addressing the global plastic crisis and protecting environmental and human health.

New Plastic Materials Approaches in Industrial Engineering

Industrial engineering is increasingly focused on sustainability, high-performance manufacturing, and circular economies. This chapter structure explores how *New Plastic Materials (NPMS),* ranging from biodegradable polymers to smart composites, are being integrated into industrial processes.

Introduction: The Evolution of Plastics in Industry

In the next paragraphs we shall discuss three aspects:

- *The shift from commodity to functional* which is related to moving beyond simple packaging processes to high-stress industrial applications when using plastic materials.
- *Industrial engineering requirements* which deal with answering the question: how materials impact production speed, cost-efficiency, and machine lifespan?
- *The green transition* that comes with regulatory pressures (ISO standards, carbon footprints) driving material innovation.

The industrial engineering landscape is witnessing a significant shift from traditional metals (steel, aluminum, bronze) toward high-performance polymers, known as New Plastic Materials (NPMS) or engineering thermoplastics. These materials are increasingly chosen for high-stress, high-temperature, and functional applications, moving beyond their traditional role as cheap alternatives to become primary structural solutions.[6]

[6] More details at https://diode.sa/engineering-plastics-vs-metal-components-in-industrial-applications/, https://www.grandviewresearch.com/industry-analysis/high-performance-plastics-market-report, and https://www.piedmontplastics.com/blog/mechanical-engineering-applications

Key drivers of the described paradigm shift to NPMS are:[7]

- *Performance under stress.* Modern engineering plastics like PEEK (polyetheretherketone), PPS (polyphenylene sulfide), and PI (polyimide) exhibit high mechanical strength, creep resistance, and dimensional stability, allowing them to operate under heavy structural loads.
- *Weight reduction and efficiency.* High-performance plastics offer superior strength-to-weight ratios compared to metal, essential for electric vehicles (EVS) and aerospace applications seeking fuel efficiency and enhanced battery range.
- *Durability and environmental resistance.* Polymers provide inherent resistance to corrosion, moisture, and chemicals, often outlasting metals in harsh environments, such as marine and chemical processing.
- *Reduced friction and maintenance.* Many engineering plastics, including UHMWP and nylon, offer self-lubricating properties, reducing the need for external lubricants and decreasing maintenance in bearing and gear applications.
- *Manufacturing flexibility.* Advanced fabrication techniques, including 3D printing and precise injection molding, enable the creation of complex, multi-functional parts, streamlining assembly.

Transition to high-stress integration (considerations based on companies reports and industry trends)[8] could be associated with the following aspects:

- *Automotive and aerospace.*[9] High-performance polymers are replacing traditional metals in engine components, brake pads, chassis, and door modules. PPS and PEEK can operate continuously at high temperatures (exceeding 150°C–200°C), making them suitable for under-the-hood applications.

[7] According to https://plastiservice.com/en/high-performance-engineering-plastics-for-industry/; more details at https://www.epol.net.au/blog/56-advantages-of-using-engineering-plastics-over-metals-in-modern-engineering

[8] More details at https://www.mordorintelligence.com/industry-reports/glass-fiber-reinforced-polymer-gfrp-market

[9] More details at https://aipprecision.com/latest-aerospace-polymer-research-reveals-surprising-material-properties/

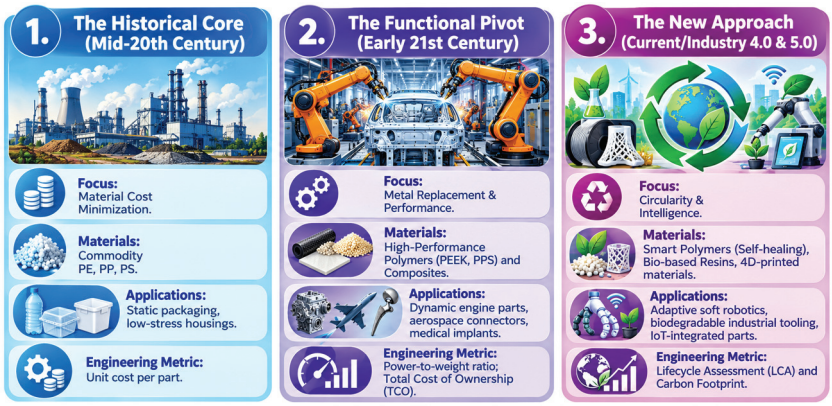


FIGURE 3.8 The Industrial Polymer Evolution Model

NOTES Created using ChatGPT.

- *Material handling and packaging.* Engineering plastics are now standard in structural applications where high wear resistance and structural integrity are necessary over long-life cycles.
- *Medical and industrial.* Specialized polymers are replacing metal in biomedical implants, surgical tools, and industrial machinery due to their high biocompatibility and ability to be sterilized.

While metals remain superior in extreme rigidity and temperature scenarios, the strategic integration of NPMS offers superior corrosion resistance, weight savings, and design flexibility, making them the preferred choice for modern industrial innovation. In synthesis, Figure 3.7 schema illustrates how the shift in material selection influences the three pillars of industrial engineering: *performance, sustainability,* and *process economics.* The considerations and the synthesis in Figure 3.8 shows that the 'New Approach' is not just about a different material (as new type of plastics are!), but a complete redesign of the *industrial lifecycle.* Furthermore, we shall explore the transition from commodity-grade usage to functional, high-stress integration (the literature provided by industrial and consultant companies were valuable to address the following topics).

The Shift from Commodity to Functional

For decades, the industrial use of plastics was dominated by high-volume, low-cost applications such as packaging, simple housings,

and non-structural components. These were primarily *commodity plastics* (e.g., standard Polyethylene or Polystyrene). Today, the focus has shifted toward *functional polymers.* These materials are engineered at the molecular level to exhibit specific properties (Rothman & Ryan, 2023; Fink, 2024):

- *High strength-to-weight ratio.* Essential for reducing the inertia of moving parts in high-speed machinery.
- *Chemical and thermal resistance.* Enabling plastics to operate in environments previously reserved for stainless steel or ceramics.
- *Tribological excellence.* New plastics often possess self-lubricating properties, significantly reducing the maintenance requirements for bearings and gears.

Industrial Engineering Requirements

In the context of industrial engineering, a material is only as good as its impact on the *Production System*. The adoption of new plastic materials is driven by three core industrial pillars (Rothman & Ryan, 2023; Fink, 2024):

- *Production Speed.* Advanced thermoplastics allow for faster injection molding cycles and 'cool-to-touch' handling, reducing the bottleneck in assembly lines.
- *Cost-Efficiency.* While the raw material cost of high-performance plastics (like PEEK) is higher than steel, the *Total Cost of Ownership (TCO)* is often lower due to reduced machining costs, lower shipping weights, and longer component lifespans.
- *Machine Lifespan.* Plastic components act as natural vibration dampeners. By integrating plastic mounts or connectors, industrial engineers can reduce the mechanical stress on the entire system, preventing premature fatigue in more expensive metal frames.

The Green Transition and Regulatory Drivers

Industrial engineering no longer operates in a vacuum of 'efficiency at any cost.' The modern engineer must navigate a complex web of environmental mandates (Rothman & Ryan, 2023; Fink, 2024):

- *Decarbonization.* National and international policies (such as the

EU Green Deal) are forcing industries to account for the carbon footprint of their raw materials.

- *Circular economy standards.* New plastics are being designed with 'End-of-Life' (EOL) strategies in mind. This involves moving away from the linear 'Take-Make-Waste' model toward a system where plastic industrial components are fully re-processible.
- *ISO 14001 and beyond.* Compliance with environmental management standards is becoming a prerequisite for global supply chain participation, making 'green' plastics a strategic business asset rather than just an ethical choice.

The NPMS refers not just to the chemical novelty, but to the *strategic application* of these materials to solve modern industrial challenges, balancing mechanical performance with environmental responsibility.

Advanced Thermoplastic Elastomers (TPES) and High-Performance Polymers

The present sub-chapter will be focus on the following three aspects:

- *Next-gen materials* referring to the deep dive into PEEK (Polyether ether ketone) and PPS (Polyphenylene sulfide) for extreme environments.
- *Mechanical integrity* which refers to the resistance to heat, chemicals, and mechanical fatigue in heavy machinery.
- *Considerations and debates* on replacing metal components with high-performance plastics to reduce weight and energy consumption.

In modern industrial engineering, the 'Polymer Pyramid' is a hierarchical framework used to classify plastic materials based on a combination of *performance, cost,* and *manufacturing volume.* It helps engineers select the appropriate material by balancing required properties, such as heat resistance, mechanical strength, and chemical durability, against the cost of the material. As can be seen in Figure 3.9, as you move from the base to the top of the pyramid, the materials generally increase in price and performance while decreasing in annual production volume. Thus, the three tiers of the Polymer Pyramid are:[10]

[10] More explanations are provided by https://invibio.com/en/blog/2017/high-performance-polymers

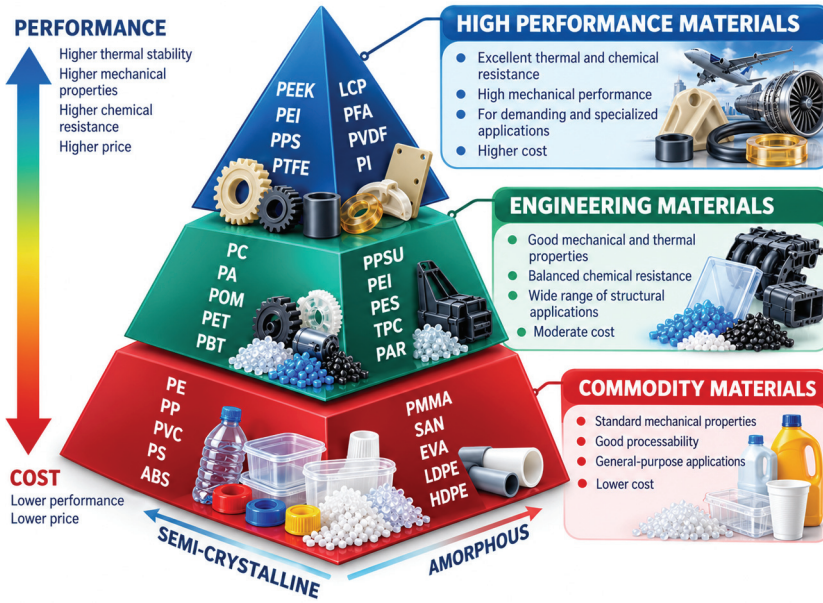


FIGURE 3.9 Example of Polymer Pyramids

NOTES Created using ChatGPT, based on Goodfellow (2025).

1. Commodity polymers (base of the Pyramid):
   - *Characteristics.* Lowest cost, high-volume production, relatively low heat resistance, and moderate mechanical properties.
   - *Examples.* Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC).
   - *Uses,* Packaging, disposable labware, household items, plastic bags.
2. Engineering polymers (middle tier):
   - *Characteristics.* Mid-range cost and performance. They offer enhanced mechanical strength, better thermal stability, and higher chemical resistance than commodity plastics.
   - *Examples.* Polycarbonate (PC), Polyamide (PA, 'Nylon'), Polyoxymethylene (POM, 'Acetal').
   - *Uses.* Fluidic systems, precision components, automotive parts, machine parts.
3. High-performance polymers (top tier/apex):
   - *Characteristics.* Highest cost and performance, designed for

extreme environments. These materials often withstand high temperatures, high stress, and aggressive chemicals.
- *Examples.* Polyetheretherketone (PEEK), Polytetrafluoroethylene (PTFE/Teflon), Polyimide (PI), Polyamide-imide (PAI).
- *Uses.* Aerospace, medical implants, high-end electronics, advanced tribological (wear/friction) applications.

As a conclusion to the debate, the key factors considered in the Polymers Pyramid are:

- *Performance (top-to-bottom).* Service temperature, mechanical strength, rigidity, and chemical resistance.
- *Cost and volume.* High-performance polymers (HPPS) are typically more difficult to produce and manufactured in lower volumes, making them more expensive than commodity plastics.
- *Structure.* Often classified by molecular order (amorphous vs. semi-crystalline), which influences their ability to handle stress and heat.

Imidized plastics are sometimes considered a specialized, even higher-performing, tier above or within the high-performance category.[11] Imidized plastics are ultra-high-performance polymers designed for extreme environments, featuring superior thermal stability, high load-bearing strength, and chemical resistance.[12] Key types of Imidized plastics are:

- *Polyimide (PI).* Known for extreme temperature resistance, it is often non-melting and processed via powder metallurgy or sintering.
- *Polyamide-imide (PAI).* Offers the highest performance among melt-processable plastics, combining exceptional strength and wear resistance.
- *Polybenzimidazole (PBI).* Known for having the highest heat resistance and compressive strength of any thermoplastic.

Top characteristics and applications of imidized plastics are:

[11] More information at https://www.copeplastics.com/knowledge-base/blog/plastic-material-selection-engineering-high-performance-and-imidized-plastics/

[12] For more information on high-temperature options, see Curbell Plastics' Imidized Materials guide available at https://www.curbellplastics.com/resource-library/material-selection-tools/thermoplastics-triangle/imidized-materials/

- *Thermal resistance.* Retains rigidity and strength in temperatures exceeding;
- *Wear and load.* Excellent compressive strength and creep resistance;
- *Industry use.* Widely used in aerospace components, semiconductors, high-performance bearings, and electrical connectors;
- *Fabrication.* Available in sheet, rod, or custom molded parts.

In the next paragraphs, we shall focus on the apex of that pyramid: materials that provide the thermal and mechanical stability required to displace traditional metals and ceramics in heavy-duty environments.

Next-Generation High-Performance Polymers (HPPS)

High-performance polymers are defined by their ability to maintain mechanical integrity at sustained operating temperatures exceeding 150°C. As of 2026, two materials dominate the industrial landscape (González, 2022; Panin et al., 2020):

1. *PEEK (Polyether ether ketone):*
   - *Properties.* Exceptional thermal stability (up to 250°C continuous use), low outgassing, and incredible fatigue resistance.
   - *Industrial application.* Used in semiconductor wafer handling, aerospace fuel connectors, and deep-sea oil extraction equipment where failure is not an option.
2. *PPS (Polyphenylene sulfide):*
   - *Properties.* Inherently flame-retardant with superior chemical resistance to almost all known solvents at temperatures below 200°C.
   - *Industrial application.* Ideal for 'under-the-hood' automotive components, pump housings, and valve bodies in chemical processing plants.

Advanced Thermoplastic Elastomers (TPES)

TPES combine the processing advantages of thermoplastics with the flexible properties of rubber. The latest approach in industrial engineering involves moving beyond standard TPES to specialized grades (Holden, 2024; Li et al., 2026):

- *High-Heat TPVS (Thermoplastic Vulcanizates)* which are increasingly replacing EPDM rubber in seals and gaskets due to their su-

TABLE 3.3 A Comparison Between Traditional Metal (Steel/Al) and High-Performance Polymers

Feature	Traditional metal (Steel/Al)	High-performance polymers
Weight	High (High inertia)	Low (Up to 60% reduction)
Corrosion	Requires coating/plating	Inherent resistance
Lubrication	Often requires external grease	Frequently self-lubricating
Manufacturing	Multi-step machining/casting	Single-step injection molding
Maintenance	High (Rust/Wear)	Low (High fatigue life)

perior 'compression set' (the ability to return to original shape) at high temperatures.

- *Conductive and dielectric TPES,* engineered with carbon nanotubes or metallic fillers, these polymers are used in the electronics industry to provide flexible EMI (Electromagnetic Interference) shielding.
- *Bio-based TPES,* emerging as a sustainable alternative for soft-touch industrial grips and vibration isolators, utilizing renewable feedstocks without compromising tensile strength.

Metal-to-Plastic Conversion: Strategic Advantages

The transition from metal (aluminum, steel, brass) to High-Performance Polymers (HPPS) is no longer just about weight; it is a strategic maneuver to optimize the *Total Cost of Ownership (TCO)* (Kapelevich, 2020; Gundeti & Lingala, 2023). The transition from traditional metals like aluminum, steel, and brass to HPPS in manufacturing is a strategic move to optimize the Total Cost of Ownership (TCO), reducing costs by up to 25% by addressing lifecycle expenses beyond just raw material prices. While metal components are often cheaper to procure initially, HPPS offer lower overall costs through increased service life, reduced maintenance, faster manufacturing cycles, and eliminated secondary finishing processes.[13] For the relevance of the topics, in Table 3.3, the features of traditional metal are centralized in comparison with the one for the high-performance polymers.

Key Total Cost of Ownership (TCO) advantages of HPPS over metals are presented in the following.[14]

[13] More details at https://aipprecision.com/the-advantage-of-plastics-over-metals-for-custom-parts/

[14] More information at https://www.piedmontplastics.com/blog/polymer-vs-metal

- *Reduced manufacturing costs.* HPPS often eliminate the need for post-processing steps like machining, drilling, or painting, as they can be molded into complex, finished shapes in shorter cycles.
- *Lower maintenance and longer lifespan.* Unlike metal, which is prone to corrosion, HPPS are inherently resistant to harsh chemicals and corrosion, lasting 3x to 5x longer in demanding environments, which drastically lowers maintenance downtime.
- *Reduced operational costs (energy and logistics).* Being up to 80% lighter than steel, HPPS significantly reduce logistics costs and fuel consumption in automotive and aerospace applications.
- *Improved performance and functionality.* HPPS offer superior design flexibility, allowing engineers to combine multiple components into a single part, reducing assembly time and costs.

Furthermore, metal-to-plastic conversion has a strategic advantages and impact on industry:[15]

- *Automotive/EVS.* The push for lighter vehicles for better range is driving adoption, where polymers replace metals in powertrain and structural applications.
- *Aerospace.* High-performance polymers (e.g., PEEK) are replacing metal parts in structural applications, saving 40% in weight while maintaining, or exceeding, mechanical performance.[16]
- *Electronics/Semiconductors.* HPPS offer thermal insulation and superior chemical resistance to wafer cleaning chemicals, reducing costs and extending equipment life.

This strategic pivot is not just about replacing metal, but rather a 'functional rethinking' that utilizes advanced plastic material properties to achieve better efficiency and lower costs across the entire product lifecycle.

Mechanical Integrity and Reliability

For industrial engineers, the primary concern with 'new' plastics is *creep* (deformation under constant stress) and *fatigue.* Advanced ap-

[15] More details at https://www.themanufacturer.com/articles/high-performance-polymers-replacing-metals-demanding-applications/

[16] More information at https://fluorocarbon.co.uk/resources/blog/high-performance-polymers-vs-metal-alloys-in-aerospace/

proaches involve the use of *carbon-fiber reinforcements* within the polymer matrix. By aligning these fibers during the injection molding or 3D printing process, engineers can create anisotropic parts that are rigid in the direction of the primary load while remaining lightweight and dampening vibrations, a feat metal alloys cannot easily replicate.

Industrial insight. The successful implementation of these materials relies on *Early Design Involvement.* Engineers must design for the *polymer's* strengths (like part consolidation) rather than simply mimicking a metal part's geometry.

Sustainable and Bio-based Plastic Solutions

The preset sub-chapter will be focus on the following three aspects:

- *Biopolymers in manufacturing.* Utilizing PLA, PHA, and bio-based PE in industrial workflows.
- *Recyclability by design.* Designing plastic components for easy disassembly and 'closed loop' recycling.
- *Degradation control.* Engineering plastics with predictable lifespans for temporary industrial tooling.

As industrial engineering moves toward 'Net Zero' targets, the selection of plastic materials is no longer based solely on mechanical performance but on their environmental footprint. This section explores how bio-based resins and circular economy strategies are being integrated into large-scale industrial manufacturing. Furthermore, the integration of bio-based resins and circular economy strategies into large-scale industrial manufacturing is driven by the imperative to achieve 'Net Zero' targets, moving beyond traditional mechanical performance metrics to prioritize environmental footprint. This shift involves adopting renewable feedstocks, enhancing recycling technologies, and implementing systemic changes to production, use, and end-of-life (EOL) management (Bauer et al., 2022). Several aspects of interest in approaching this topic will be presented in the following:

1. *Integration of bio-based resins.* Bio-based plastics are increasingly being integrated as sustainable alternatives to petroleum-based polymers, with applications in automotive, packaging, and structural materials:[17]

[17] More information at https://joint-research-centre.ec.europa.eu/jrc-news-and

- *Renewable Feedstocks.* Bio-based resins are derived from biomass sources, including agricultural by-products (sugarcane, cellulose), vegetable oils, and non-edible residues (lignin).
- *'Drop-in' solutions.* A key strategy for large-scale adoption is the use of 'drop-in' bio-based polymers (e.g., Bio-PET, Bio-PE). These are chemically identical to conventional plastics, allowing them to be processed by existing machinery without requiring changes to manufacturing, handling, or recycling infrastructure.
- *Performance enhancement.* Advancements in bio-based composites (e.g., lignin-incorporated vinyl ester) have shown improvements in stiffness and thermal stability, enabling them to meet the rigorous performance requirements of engineering applications.
- *Mass balance approach.* To scale production, industries are employing a mass balance approach, where bio-based feedstocks are blended with fossil feedstocks in existing production lines. This allows companies to certify the bio-based content and reduce Scope 3 emissions without requiring entirely new supply chains.

2. *Circular economy strategies in manufacturing.* Circular strategies focus on keeping materials in use, reducing pollution, and creating closed-loop systems, often aided by Industry 4.0 technologies (Nwamekwe & Chikwendu, 2025; Ijimdiya et al., 2026):
   - *Design for recycling (DfR).* Industrial engineers are prioritizing the use of mono-materials and designing products that can be easily disassembled, improving the efficiency of mechanical recycling.
   - *Advanced recycling technologies* (Rosenboom et al., 2022):
     - *Mechanical Recycling.* The most established method, which shreds, melts, and reforms plastic waste. It is increasingly being adapted to handle post-industrial recyclates (PIR) and post-consumer recyclates (PCR) to maintain high-quality material flows.
     - *Chemical recycling (depolymerization).* Emerging as a criti-

-updates/bio-based-plastics-technology-readiness-and-high-cost-key-barriers-wide
-use-2026-03-03_en and https://www.cytivalifesciences.com/en/us/behind
-biopharma/stories/bio-based-polymers-towards-net-zero-in-single-use
-bioprocessing-10002

cal solution for mixed or contaminated plastics. It breaks down polymers into monomers, creating virgin-quality materials, which is essential for industries with strict safety requirements (e.g., medical, food packaging).

- *Take-back systems and producer responsibility (EPR).* Companies are adopting take-back systems for industrial waste (e.g., sprues, failed parts) to re-introduce materials directly into the production line.
- *Digitalization and AI.* Technologies such as Artificial Intelligence (AI) and the Internet of Things (IOT) are being deployed for automated sorting, tracing, and monitoring, enabling a more precise and efficient separation of plastics, which enhances the quality of recycled outputs.

3. *Challenges in large-scale integration.* Despite progress, scaling up these solutions faces significant hurdles:
   - *Economic disparity.* Bio-based plastics are currently 1.5–2 times more expensive to produce than fossil-based alternatives.
   - *Supply chain maturity.* The supply chain for bio-based feedstock is still less developed compared to fossil fuels, leading to potential feedstock competition with food production.
   - *Infrastructure limitations.* Existing waste management systems often lack the capacity to sort bio-based and biodegradable plastics separately, leading to contamination in conventional recycling streams.

By utilizing a combination of bio-based materials and advanced recycling methods, industrial engineering is moving toward a regenerative model, reducing reliance on finite resources while mitigating plastic pollution.[18]

Biopolymers in Industrial Manufacturing

The 'New Approach' distinguishes between *bio-based* (source) and *biodegradable* (end-of-life). In an industrial context, engineers are prioritizing materials that offer the durability of petroleum plastics but are derived from renewable feedstocks.

Key materials and strategies are presented in the following (Iwata, 2015; Morais et al., 2025; Shahar et al., 2025; Rosenow et al., 2025):

- *Bio-based drop-ins.* Bio-PET, Bio-PE (polyethylene), and Bio-PA

[18] More details at https://kaizen.com/insights/circular-economy-chemical-plastic/

(polyamides) are chemically identical to petrochemical counterparts. They are derived from renewable sources like sugarcane or corn but are not biodegradable, allowing them to fit into existing, highly durable, and recyclable plastic infrastructure.

- *High-performance bioplastics.* Polytrimethylene Terephthalate (PTT) and Polyethylene Furanoate (PEF) are highlighted for superior mechanical strength and thermal stability, acting as replacements for PET in packaging.
- *Reinforced biocomposites.* Engineers increase the durability of biopolymers like PLA (polylactic acid) by adding natural fibers (e.g., hemp, flax, jute) or mineral additives to achieve required structural integrity for automotive, electronics, and construction applications.
- *Functional additives.* The incorporation of natural fillers and specialized additives improves mechanical properties, such as tensile strength and water vapor barrier performance, to make bio-based materials suitable for long-term usage rather than just short-term packaging.
- *Renewable feedstocks.* Efforts are increasingly focused on using agricultural and non-edible biomass residues (lignocellulosic waste) instead of food crops to improve sustainability.

These durable bio-based plastics are targeted to replace conventional petrochemical plastics in durable goods, such as vehicle parts, electronics, and consumer appliances, while reducing dependency on fossil fuels (Iwata, 2015; Morais et al., 2025; Shahar et al., 2025; Rosenow et al., 2025).

Recyclability by Design (The Circular Approach)

Modern industrial engineering focuses on *Design for Disassembly (DfD).* The goal is to ensure that plastic components do not end up in landfills but remain within a closed-loop system (Heisel et al., 2025; Moujoud et al., 2025). Two initiatives are practically use in this case:

- *Mono-material engineering.* To simplify recycling, engineers are designing complex assemblies (like pumps or valves) using a single polymer family (e.g., all-polypropylene systems). This eliminates the need for labour-intensive material separation during recycling.

- *Compatibilizers.* New chemical additives are being used to allow the blending of traditionally incompatible recycled plastics, enabling 'upcycling' where waste plastic is turned into high-strength industrial pallets or crates.

Degradation Control and Managed Lifespans

A unique industrial approach involves 'programmed' degradation. Instead of demanding that every part lasts forever, engineers are selecting materials with lifespans tailored to the machine's maintenance cycle. This approach, often termed 'Degrade to Function' (DtF) or engineered degradation, marks a shift from designing solely for maximum durability to designing for controlled, timely expiration. By incorporating additive agents or selecting specific biopolymers, materials are created to serve their purpose and then break down under specific environmental conditions.[19] Several solutions and initiatives will be presented in the following (UV, thermal, or chemical) (Lu et al., 2024; Eremin et al., 2026):

- *Predictable aging.* Using additives that trigger breakdown only under specific UV, thermal, or chemical stimuli. This is useful for temporary industrial supports or sacrificial parts used during the manufacturing process. Engineers use additives to trigger the breakdown of materials at the end of their useful life. This is not failure; it is designed obsolescence for sustainability. The solutions are:
  - *UV/thermal/chemical triggers.* Materials can be engineered to remain stable under normal operational conditions but degrade rapidly when exposed to specific stimuli, such as UV radiation (photodegradation) or high heat (thermocatalytic degradation).
  - *Sacrificial industrial parts.* Temporary components, such as structural supports in complex machinery, protective coatings, or agricultural films, can be tailored to degrade, simplifying removal or eliminating the need for manual disassembly, particularly for parts that are hard to access or clean.
  - *Contrived durability.* This allows for the selection of cheaper or lighter materials that perfectly match the required mainte-

[19] More details at https://www.newscientist.com/article/2506104-plastic-can-be-programmed-to-have-a-lifespan-of-days-months-or-years/

nance cycle of a machine, rather than over-engineering parts with excessive lifespan.

- *Compostable industrial packaging.* Moving away from traditional stretch wraps to bio-polymer films that can be processed in industrial composting facilities alongside organic factory waste. The move toward sustainable industrial operations involves replacing traditional petroleum-based plastics with bio-polymer films. Solutions in this case are (Sokač Cvetnić et al., 2026):
  - *Bio-polymer films.* Materials such as Polyhydroxyalkanoates (PHAS) or Polylactic Acid (PLA) are used. These are derived from renewable resources and are designed to break down in industrial composting facilities rather than persisting as waste.
  - *Closed-loop disposal.* Unlike traditional plastics that contaminate recycling streams, these materials can be collected along with organic factory waste and processed via industrial composting, which provides the necessary thermophilic (55°C–75°C) conditions for degradation.
  - *Advantages over traditional packaging.* These materials reduce microplastic contamination, lower carbon footprints, and allow for easier disposal of packaging contaminated with organic materials, such as food or agricultural products.

Summary of industrial applications refers to the manufacturing field (sacrificial preforms and structural supports for machining fragile, thin parts); agriculture (mulch films that decompose after harvesting); logistics (stretch wraps and protective industrial films) and electronics (degradable protective coatings). In conclusion, this strategy moves the industry closer to a circular economy, where the end-of-life of a material is as planned as its beginning

Life Cycle Assessment (LCA) Comparison

Industrial engineers now use LCA software to quantify the 'Cradle-to-Gate' impact of material choices.[20] Furthermore, industrial engineers can use this information to make sustainable design decisions based on specific performance and environmental targets (Marciniak & Moejko-Ciesielska, 2021):

[20] See https://www.arbor.eco/blog/what-is-cradle-to-gate-in-carbon-calculations-carbon-101

TABLE 3.4 Data to Optimize the 'Cradle-to-Gate' Impact

Material type	Feedstock	CO_2 Footprint	Recyclability	Typical industrial use
Traditional PP	Fossil Fuels	High	Moderate	Storage bins, piping
Bio-PE	Sugarcane	Low/Neutral	High	Flexible tubing, seals
Recycled PET	Post-consumer	Moderate	High	Protective housings
PHA	Bacteria/Waste	Very Low	Biodegradable	Single-use sensors, caps

- *Lowest carbon footprint* – *PHA* (produced via bacteria/waste) offers the lowest environmental impact ('Very Low') and provides the advantage of being biodegradable, making it suitable for single-use components like sensors or caps.
- *Renewable and high recyclability* – *Bio-PE* (sourced from sugarcane) provides a low/neutral carbon footprint and high recyclability, acting as a direct, sustainable alternative to traditional plastics for flexible applications.
- *Circular economy approach* – *Recycled PET* utilizes post-consumer waste to achieve a moderate CO_2 footprint and high recyclability, ideal for durable protective housings.
- *Traditional high-impact* – *Traditional PP* relies on fossil fuels and has a high carbon footprint, typically used for durable goods like storage bins and piping.

Table 3.4 allows for a direct comparison of feedstock sustainability, emission impact, and end-of-life options (recyclability vs. biodegradation) to optimize the 'Cradle-to-Gate' impact.

Industrial insight. The challenge for 2026 is overcoming the 'Green Premium' the higher initial cost of biopolymers. However, as carbon taxes increase, the *total life-cycle cost* of sustainable plastics is becoming more competitive than fossil-fuel-based alternatives.

Smart Plastics and Functional Additives

The preset sub-chapter will be focus on the following topics:

- *Conductive polymers* referring to integrating plastics that can conduct electricity or dissipate static for electronics manufacturing.

- *Self-healing materials* with the focus on polymers that can repair micro-cracks autonomously, reducing maintenance downtime.
- *Shape Memory Polymers (SMPS)* discussing applications in 'soft robotics' and adaptive industrial grippers.

In the era of Industry 4.0, 'passive' materials are being replaced by 'active' ones. Smart plastics are polymers engineered to respond dynamically to external stimuli, such as temperature, stress, or electrical fields, integrating sensing and actuation directly into the material's structure.

Conductive Polymers and EMI Shielding

Traditionally, plastics have served as insulators. However, by incorporating functional additives like *Carbon Nanotubes (CNTS), Graphene,* or *Metallic Nanofibers,* industrial engineers can now create plastics that manage electricity:

- *ESD (Electrostatic Discharge) Protection* vital for cleanrooms and semiconductor manufacturing where static can destroy sensitive components.
- *Integrated circuitry.* Using conductive polymers in *In-Mold Electronics (IME)* to print sensors and buttons directly into plastic housings, reducing the need for separate wiring and heavy copper harnesses.
- *EMI/RFI shielding.* Replacing heavy metal housings in electric vehicle (EV) components with lightweight, conductive plastic shields to block electromagnetic interference.

The above-mentioned additives create conductive pathways within the plastic, which are essential for applications ranging from electrostatic discharge (ESD) protection to electromagnetic interference (EMI) shielding. In the following there will be described the *key additives and their roles* (Castellino et al., 2016; Fenta & Mebratie, 2024):

- *Carbon Nanotubes (CNTS).* Renowned for their exceptionally high aspect ratio and electrical conductivity, adding small amounts (0.1% to 10% by weight) can create a conductive network, often outperforming traditional fillers like carbon black.
- *Graphene.* A two-dimensional sheet of carbon atoms, graphene is highly efficient at imparting conductivity and enhancing the strength of polymers.

- *Metallic Nanofibers/Powders.* Metals such as nickel, copper, or silver (often in the form of fibers or powders) are added to polymers to achieve high conductivity, particularly when shielding sensitive electronic components.

Explaining the mechanism, there should be pointed about percolation and conductivity. The transition from insulator to conductor occurs based on the *percolation threshold,* which is the minimum concentration of filler required to form a continuous, connected 3D network throughout the plastic matrix. Once this threshold is met, the material's electrical conductivity can increase by several orders of magnitude.

Regarding their benefits and applications, conductive plastics are becoming increasingly popular as replacements for metals because they offer:

- *Reduced weight and cost.* Lower density than metal, making them ideal for automotive and aerospace components.
- *Design flexibility.* Easily molded into complex shapes using standard techniques like injection molding.
- *Anti-static/ESD prevention.* Used in packaging for electronics to prevent harmful static discharge.
- *EMI shielding.* Used in electronic housings to prevent interference, especially in 5G and high-speed data devices.
- *Smart textiles.* Used to create flexible electronic circuits and wearable sensors.

Manufacturing challenges. While effective, achieving uniform dispersion of these nanofillers is difficult, as they tend to agglomerate, which can reduce their conductive efficiency. Furthermore, high filler concentrations can sometimes compromise the mechanical strength or increase the viscosity of the polymer, making them harder to process (Fenta & Mebratie, 2024).

Self-Healing Polymers

Maintenance downtime is a major 'hidden cost' in industrial engineering. Self-healing plastics utilize either micro-encapsulated healing agents or reversible chemical bonds (vitrimers) to repair damage.

- *The mechanism.* When a micro-crack occurs, embedded microcapsules rupture, releasing a 'healing' resin that polymerizes and seals the crack.
- *Industrial use.* Seals, gaskets, and protective coatings for underwater or underground infrastructure where manual repair is logistically difficult or impossible.

There are two primary approaches to self-healing (Terryn et al., 2021; Tian et al., 2025):[21]

- *Extrinsic (Micro-encapsulated).* Healing agents (such as monomer resins) are embedded within microcapsules inside the polymer matrix. When a micro-crack occurs, it ruptures the capsules, releasing the resin. This agent fills the crack, contacts an embedded catalyst, and polymerizes to seal the damage.
- *Intrinsic (vitrimers/reversible bonds).* The material uses reversible chemical bonds (covalent adaptable networks) or dynamic noncovalent bonds (e.g., hydrogen bonds). These bonds can break and reform, often triggered by heat, UV light, or water, allowing the material to repair itself repeatedly.

Industrial use and applications is very interesting. Self-healing polymers are widely adopted in industries requiring high reliability and low maintenance (Golonka & Laska, 2025):

- *Seals and gaskets.* Self-healing elastomeric seals are used in automotive, oil and gas, and aerospace applications to maintain pressure-tightness and prevent fluid leakage.
- *Protective coatings.* Used on metal substrates to prevent corrosion by sealing micro-cracks, protecting pipelines, and underwater equipment.
- *Aerospace and infrastructure.* Applied in composite airplane skins to prevent fatigue and delamination, as well as in underground/underwater pipes and cables.
- *Industrial logic.* The adoption of self-healing materials can lead to significant cost savings by extending service life by up to 75%,

[21] More details at https://www.azom.com/article.aspx?ArticleID=7902; see also https://www.cunninghaminc.org/the-future-of-water-infrastructure-self-healing-coatings/

TABLE 3.5 The Stimulus-Response Loop in Smart Plastics

Stimulus	Material response	Industrial application
Electrical current	Change in conductivity or shape	Soft robotics; Integrated sensors
Mechanical stress	Colour change (Mechanochromic)	Visual structural health monitoring
Temperature	Shape memory recovery	Adaptive ventilation; Thermal fuses
Micro-fracture	Autonomic resin release	Self-healing pressure vessels

preventing multimillion-dollar fractures, and cutting preventative maintenance in composite-rich structures by roughly 40%.

Shape Memory Polymers (SMPS) and 4D Printing

Shape Memory Polymers (SMPS) can be 'programmed' to return to a pre-defined shape when triggered by heat, light, or moisture. When combined with 3D printing, this is referred to as *4D Printing*.

- *Adaptive grippers.* Robotic arms equipped with SMP 'fingers' that can adjust their grip strength and shape based on the temperature of the object being handled.
- *Self-deploying components.* Industrial parts that are shipped flat to save space and 'unfold' into their functional geometry once they reach the operating temperature of the factory floor.

SMPS are stimuli-responsive smart materials that can be 'programmed' to temporarily hold a deformed shape and return to their original, permanent shape when triggered by external stimuli such as heat, light, moisture, or pH changes. When this material behaviour is integrated into 3D printing, where the printed object can transform its shape, properties, or functionality over time, it is referred to as *4D Printing*. Key applications of 4D-printed SMPS include (Pittala et al., 2026; Razzaq et al., 2022; Yan et al., 2023; Lin et al., 2024):

- *Adaptive grippers.* Robotic arms or soft grippers equipped with SMP 'fingers' can be designed to conform to the shape of an object at high temperatures, then lock that shape upon cooling to securely hold it. These grippers can adjust their grip strength, enabling delicate handling of fragile objects or secure lifting of heavy, irregularly shaped items.

- *Self-deploying components.* Industrial parts can be printed in a flat or compact 'temporary' state, allowing for efficient shipping and space saving. Once they reach their destination (e.g., the operating temperature of a factory floor), they are triggered to 'unfold' or expand into their functional, permanent geometry. This is particularly useful in aerospace for deploying large antennas or solar panels, and in biomedicine for self-expanding stents.
- *Smart actuators and robotics.* SMPS can function as soft actuators in soft robotics, enabling motion through shape-changing mechanisms.
- *Biomedical devices.* These include self-tightening sutures, adaptive scaffolds for tissue engineering, and drug delivery devices that change shape based on body temperature or moisture to release medication.
- *Information encryption/metamaterials.* 4D-printed SMPS can be used as information carriers that reveal hidden text or images only when triggered by specific stimuli (e.g., heat or light), or as metamaterials with tunable mechanical properties.

The 4D printing of SMPS offers advantages like low density, low cost, designability, and the ability to fabricate highly complex, personalized structures on demand.

Functional Additives: Beyond Strength

Functional additives are transforming standard resins by imparting specialized properties beyond mere mechanical strength, enabling plastic to solve critical engineering challenges in challenging environments. Doping, or incorporating these additives during compounding or manufacturing, directly addresses bottlenecks in safety, durability, and hygiene. Here is a breakdown of the three key functional additives mentioned:[22]

1. *Antimicrobial additives.* Silver or copper-ion-based additives are integrated directly into the polymer matrix, providing a durable, long-lasting, and self-sanitizing surface that prevents biofilm,

[22] More details at https://www.elixance.com/en/functional-additives and https://plastics-rubber.basf.com/asiapacific/en/plastic_additives/products/functional-additives

fungi, and bacterial growth (Alojaly & Benyounis, 2022; Patel et al., 2022; Okur et al., 2025):

- *Mechanism.* When exposed to moisture, these particles release silver or copper ions (Cu2+ or Ag+) that destroy microbial cell membranes and prevent reproduction.
- *Food processing application.* Critical for equipment like food containers, conveyor belts, and cutlery. These additives prevent bacteria (like *E. coli* or *Salmonella*) from forming colonies, enhancing food safety and extending the shelf-life of products.
- *Key advantage.* Unlike sprays or coatings that wear off, integrated antimicrobial agents provide consistent, lifetime protection.

2. *UV-stabilizers.* These compounds, including Hindered Amine Light Stabilizers (HALS) and UV absorbers, are essential for plastics exposed to sunlight to prevent photo-oxidation and material degradation (Todesco & Ergenc, 2002; Marturano et al., 2017; Patel et al., 2022):
   - *Mechanism.* HALS scavenge free radicals formed by sunlight, while UV absorbers convert harmful UV rays into harmless heat.
   - *Industrial application.* Used extensively in construction (pipes, window profiles, siding) and agricultural films to prevent yellowing, brittleness, and loss of mechanical strength in outdoor environments.
   - *Key advantage.* Extends the service life of outdoor plastic products by several years, often preventing up to 50% loss of mechanical properties.
3. *Halogen-free flame retardants.* These additives, often based on phosphorus, nitrogen, or inorganic minerals (like aluminium or magnesium hydroxide), ensure compliance with strict UL94 fire safety standards without the harmful, toxic smoke produced by traditional halogenated (bromine/chlorine) systems:[23]
   - *Mechanism.* They work through endothermic decomposition (cooling the surface) and the formation of a char layer that acts as a barrier against heat and oxygen.

[23] More information on https://www.psolera.com/en/news/importance-manufacturing-products-halogen-free-compounds and https://www.psolera.com/en/news/importance-manufacturing-products-halogen-free-compounds

- *Safety standards (UL 94).* They enable plastic to achieve high fire ratings (e.g., V-0) and are often designated as Low Smoke Zero Halogen (LSZH).
- *Key advantage.* These materials generate less toxic, non-corrosive smoke during combustion, making them critical for public transportation, electronics, and building interiors where human safety is paramount.

These 'New Approach' additives allow manufacturers to move from designing purely for structural integrity to creating 'intelligent' materials that offer hygiene, longevity, and high safety standards.

In conclusion, Smart plastics transform a component from a static 'part' into a 'functional system.' This reduces the mechanical complexity of machines by moving the 'intelligence' into the material itself.

Integration with Industry 4.0: Additive Manufacturing

In the present sub-chapter, there will be debated the following topics:

- *3D printing filaments.* The role of carbon-fibre-reinforced polymers in rapid prototyping and 'jigs and fixtures.'
- *Digital twins for material selection.* Using AI to predict how new plastics will behave under specific industrial stresses.
- *Mass customization.* How new plastics allow for small-batch industrial parts without expensive molds?

In the 'New Approach,' material selection is inseparable from the manufacturing process. Industry 4.0 leverages *Additive Manufacturing (AM),* commonly known as 3D printing, to move from mass production to *mass customization* and *on-demand industrial logistics.* In this new context, plastic materials will play an important role in profiling new technology performances.

The Shift from Prototyping to Industrial End-Use

The biggest misconception in industrial engineering is that 3D printing is only for prototypes. NPMS have bridged the gap to functional end-use parts (Rayna & Striukova, 2016; Mehrpouya et al., 2019; Caminero et al., 2019; Pelin et al., 2024).

- *Carbon-fiber reinforced filaments.* By embedding chopped or continuous carbon fibers into a nylon or PEEK matrix, engineers

can print parts with a strength-to-weight ratio exceeding that of 6061 aluminum. The use of *High-Performance Polymers (HPPS)* like *PEEK, PEKK,* or *Ultem,* reinforced with carbon fiber, has effectively shattered the mechanical strength barrier.

- *Metal replacement.* These composites are not just 'good enough,' they are often preferred over aluminum in aerospace or automotive sectors due to their *corrosion resistance* and superior *thermal insulation.*
- *Anisotropy control.* Engineers can now orient fiber deposition to handle specific stress loads, optimizing the part exactly where the highest forces are applied.
- *Jigs, fixtures, and tooling.* Instead of waiting weeks for a CNC-machined aluminum jig, factories now print customized ergonomic assembly tools in-house within hours, using high-impact polymers like *Tough PLA* or *Polycarbonate.* In the traditional model, an assembly line could be stalled for weeks waiting for a custom-machined tool.
- *Ergonomic customization.* Since 3D printing cost isn't tied to complexity, tools can be perfectly molded to an operator's hand or a specific part geometry. This reduces human error and physical fatigue.
- *Digital inventory.* Factories no longer need massive warehouses for spare parts. They maintain a digital twin (CAD files) and print the necessary tool only when the old one wears out, slashing overhead costs.

- *Part consolidation.* AM allows for the creation of complex internal geometries (like lattice structures or internal cooling channels) that are impossible to manufacture via injection molding. This reduces the number of components in an assembly, lowering the risk of joint failure. This is perhaps the most underrated aspect of the technology.
  Through *Design for Additive Manufacturing (DfAM),* an assembly that previously required 20 screws, gaskets, and separate components can become a single, unified part.
  - *Increased reliability.* Fewer joints mean fewer potential points of failure (leaks, vibrations, or bolts loosening over time).
  - *Thermal management.* Conformal cooling channels-which follow the internal curvature of a part-can only be made via AM.

> This can increase heat transfer efficiency by 30–50% compared to traditional CNC drilling.

As can be seen, the assertion that 3D printing is solely for prototyping is an outdated, 'prototype-only' misconception in industrial engineering that fails to account for modern advancements. *New Printable Materials (NPMS),* such as high-performance engineering plastics, advanced metals, ceramic-filled resins, and biocompatible materials, have bridged the gap, transforming additive manufacturing (AM) into a viable method for producing functional end-use parts. NPMS have shifted the industry paradigm from rapid prototyping to final production by addressing the functional, structural, and environmental limitations of earlier materials (Pelin et al., 2024).[24]

The Role of NPMS in bridging the gap. NPMS have transformed 3D printing from a prototyping tool into a production solution through several key advancements (Rayna & Striukova, 2016; Mehrpouya et al., 2019; Caminero et al., 2019):[25]

- *Engineering-grade performance.* Unlike traditional prototype plastics, new materials (such as carbon-fiber reinforced filaments, PEEK (polyetheretherketone), and PA11/PA12 nylon powder) provide the heat resistance, durability, and mechanical strength required for harsh operating environments.
- *Replacement of metal with polymers.* Advanced materials allow for the fabrication of parts that are lighter and just as strong as metal components. For example, reinforced plastics can be used in aerospace and automotive applications to improve fuel efficiency.
- *Customization and complexity.* NPMS, combined with 3D printing, enable the creation of complex, organic geometries that cannot be produced by traditional machining, such as optimized lattice structures for medical implants or optimized fuel injectors for engines.
- *Biocompatibility for healthcare.* The development of specialized

[24] More details at https://imaginarium.io/3d-printed-end-use-parts/ and https://3dactions.com/blog/3d-print-end-use-products-production/

[25] More details at https://ifactory3d.com/en/tpms-structures-in-3d-printing-revolutionary-geometries-for-lightweight-construction/ and https://formlabs.com/applications/end-use-parts/

medical-grade resins (BioMed Resins) allows for functional, long-term body contact parts like hearing aids, dental aligners, and prosthetic limbs.

- *High-volume compatibility.* The ability to print with durable powders (via Selective Laser Sintering - SLS) allows for small-batch manufacturing of functional, long-lasting parts, bypassing the need for expensive tooling.

Bridging the gap: from prototyping to functional components. While early 3D printing was defined by prototyping, NPMS have enabled the production of parts ready for final assembly (Andreacola et al., 2023):

1. *Bridging to production.* Companies can print functional end-use parts while waiting for traditional injection molding tools to be completed, reducing overall time to market.
2. *On-demand spare parts.* Industries can print discontinued or low-volume spare parts on-demand, lowering inventory costs and reducing logistical delays.
3. *Industrial jigs and fixtures.* Durable materials are used to create customized manufacturing tools that are lighter and more ergonomic than metal equivalents.

In conclusion, NPMS have fundamentally altered the landscape of industrial production. By offering superior mechanical properties, high-temperature resistance, and biocompatibility, these materials ensure that 3D-printed components now deliver the necessary performance for demanding, real-world end-use applications.[26]

Digital Twins and Material Informatics

Industry 4.0 integrates the 'Digital Twin' concept with material science. Before a single gram of plastic is melted, simulations predict the part's behaviour. By creating a dynamic, data-driven virtual replica of the printing process, manufacturers can predict behaviours and optimize designs, leading to significant reductions in material waste and development time (Židek et al., 2020; Kalidindi et al., 2022; Ali et al., 2023; Santos-Ceballos et al., 2024).[27]

[26] More details at https://www.stratasys.com/en/resources/blog/3d-printing-for-transportation/

[27] Practical debate at https://www.plasticmetalmold.com/news/how-ai-and-digital-twins-are-igniting-the-next-revolution-in-plastics-manufacturing/

The most actual topics in this dynamic field are:

1. *Predictive modeling* leverages AI and Machine Learning (ML) to simulate how specific polymers behave under varying conditions (Otieno et al., 2025; Gámez et al., 2025):
   - *Warp and shrinkage prediction.* AI models, trained on data from simulations and sensors, predict defects like warping or shrinkage based on processing parameters such as temperature, speed, and pressure.
   - *Ambient factory conditions.* Simulations can factor in factory environment variables, such as humidity and ambient temperature, which influence the polymer's solidification and thermal conductivity, thereby impacting final part dimensional accuracy.
   - *Reduced defect rates.* By anticipating these issues, manufacturers can adjust parameters, such as increasing printing speed to reduce cooling time or adjusting temperature, to prevent defects before they occur.
2. *Generative design*[28] uses AI algorithms to 'evolve' a part's shape, exploring thousands of design iterations to find the optimal balance between material usage and structural strength (Bernadi-Forteza et al., 2024; Koul, 2024; Tkachenko & Wang, 2024):
   - *Organic, bone-like structures.* The resulting geometries often look organic or 'alien,' featuring intricate, lattice-like, or porous structures that efficiently distribute stress.
   - *Additive manufacturing integration.* These complex, bone-like structures are typically impossible to create with traditional subtractive manufacturing (like machining) but are ideally produced via Additive Manufacturing (3D printing).
   - *Optimized performance.* These designs maximize strength-to-weight ratios, saving on material costs and producing lighter, more durable, and energy-efficient products (Resman et al., 2025).

This convergence of Digital Twins, AI, and material science enables a 'first-time-right' approach to 3D printing, transforming polymers into

[28] More details at https://formlabs.com/blog/generative-design/ and https://aidevdayindia.org/blogs/ai-smart-manufacturing-india/generative-design-ai-engineering-parts.html

high-performance components while minimizing waste and shortening production cycles.

Decentralized Manufacturing and the 'Digital Warehouse'

Decentralized manufacturing, enabled by high-performance plastics and digital warehousing, is transforming supply chains from linear models into agile, on-demand networks. By producing components close to the point of need using additive manufacturing (3D printing), companies can eliminate the need for physical inventory, drastically reduce logistics costs, and shrink their carbon footprint. Here is a breakdown of the three key pillars of this revolution[29] (Mehrpouya et al. 2019):

1. *Zero inventory (Digital Warehouse).* Instead of holding massive physical inventories of spare parts (many of which may become obsolete) companies are shifting to *Digital Warehouses*[30] (Calignano & Mercurio, 2023):
   - *CAD libraries.* Thousands of spare parts are stored as digital Computer-Aided Design (CAD) files, allowing for instant access and global distribution.
   - *Reduced costs and obsolescence.* This approach reduces storage costs, minimizes waste, and eliminates the risk of parts becoming obsolete before they are used.
   - *Resiliency.* Digital inventories enhance supply chain resilience, reducing dependencies on single suppliers or shipping routes.
2. *Point-of-need production (on-demand manufacturing).* When a part is required, it is printed on-site or at a nearby facility, often using industrial-grade 3D printing technologies like Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM) (Dua et al., 2021; Akbari, 2023).
   - *Logistics elimination.* By moving production to the point of consumption, companies eliminate long-distance shipping, which significantly reduces the carbon footprint associated with transport.

[29] More information at https://oqton.com/what-a-digital-warehouse-is-and-how-its-making-just-in-time-manufacturing-a-reality/ and https://www.3yourmind.com/news/7-advantages-of-distributed-manufacturing

[30] More details at https://immensa.io/beyond-warehouses-how-digital-inventories-and-additive-manufacturing-are-reshaping-supply-chains/

- *Speed.* This allows for rapid replacement of broken components, reducing machine downtime and avoiding expensive logistical delays.
- *Sustainability.* This model supports a circular economy by facilitating localized repair, reducing the need for virgin raw materials.[31]

3. *Filament standardization (high-performance plastics).* To guarantee that a part printed in Germany has the exact mechanical properties as one printed in Brazil, standardized, high-performance filaments (specifically Polyether Ether Ketone, PEEK) are essential:[32]
   - *PEEK advantages.* PEEK is a semi-crystalline thermoplastic that offers strength, chemical resistance, and thermal stability that rivals many metals, with a continuous-use temperature above 250°C.
   - *Consistent quality.* High-performance filament manufacturers ensure that their materials are produced to strict standards, allowing for reliable, repeatable results in industrial FDM printers.
   - *Challenges in consistency.* Achieving standardization requires rigorous moisture control (as PEEK is hygroscopic) and precise, high-temperature printing conditions, including heated chambers and controlled nozzle temperatures (360°C–450°C).

This technological shift allows for a 'digital component replacement' model, transforming how parts are manufactured and distributed globally.[33]

Industrial insight. The true power of Additive Manufacturing in industrial engineering is not just 'printing a shape' it is the ability to *spatially control material properties,* such as making one end of a part rigid and the other end flexible in a single production step.

[31] More information at https://www.blumorpho.com/about-us/unlocking-the-future-of-manufacturing-sustainability-decentralization-and-industry-5-0/

[32] More details at https://www.ensingerplastics.com/en/thermoplastic-materials/peek-plastic/peek-filament

[33] More details at https://immensa.io/beyond-warehouses-how-digital-inventories-and-additive-manufacturing-are-reshaping-supply-chains/ and https://www.ruiyi-cncmachining.com/advantages-and-disadvantages-of-fdm-rapid-prototyping-and-its-uses/

TABLE 3.6 The Additive Manufacturing Workflow in Industry 4.0

Stage	Action	Industrial Benefit
Design	Generative Design/Topology Optimization	30–50% weight reduction
Material Selection	Choosing Functional Polymers (e.g., ESD-safe, heat-resistant)	Application-specific performance
Simulation	Digital Twin stress & thermal analysis	Reduced failure rate and waste
Production	On-site 3D Printing (FDM, SLS, or SLA)	Eliminated lead times and shipping
Post-Processing	Chemical smoothing or heat-treating	Enhanced surface finish and strength

In conclusion, Table 3.6 synthesises the stages and new actions of Additive Manufacturing workflow related to the Industry 4.0.

Process Optimization and Life Cycle Assessment (LCA)

In this sub-chapter there will be debated the following topics:

- *Energy consumption.* Comparing the energy required to process new plastics vs. traditional metals/alloys.
- *Waste reduction.* Techniques for minimizing 'flash' and scrap in injection molding using new resin formulations.
- *Economic impact.* Analysing the long-term Return of Investment (ROI) of switching to more expensive, but more durable, modern plastics.

In industrial engineering, the transition from traditional metals to modern plastics is often driven by 'Cradle-to-Grave' efficiency, where the lower energy consumption of material processing and higher functional durability of plastics outweigh higher raw material costs. Modern plastics, particularly when injection molded with optimized techniques, offer significant waste reduction and lower total manufacturing costs, frequently achieving a 25–50% return of investment (ROI) through reduced assembly, finishing, and shipping expenses[34] (Sabate & Kendall, 2024).

[34] More practical details at https://www.rosti.com/resources/whitepapers/metal-to-plastic-conversion/ and https://www.ferriot.com/blog/benefits-of-replacing-metal-with-plastic/

1. *Energy consumption (Plastics vs. Traditional materials).* Modern plastics generally require less energy to process compared to traditional metals (aluminium, steel) and alloys, due to lower processing temperatures and the elimination of complex, multi-stage, high-heat operations[35] (Raabe, 2023; Francis, 2024; Rajendran et al., 2025).
   - *Manufacturing energy efficiency.* Injection molding of plastics requires lower temperatures than melting or casting metals. High-performance engineering plastics can replace metal in many applications while reducing energy used in the molding phase.
   - *Materialation (material substitution).* The use of lightweight plastic components in vehicles and machinery drastically reduces energy consumption during the *use* phase of the product, providing a superior Life Cycle Assessment (LCA) compared to heavier metal parts.
   - *Optimal processes.* While injection molding is energy-intensive (4–5 kWh/kg), new resin formulations are designed for lower melt viscosities, allowing for reduced barrel temperatures and shorter cycle times.
2. *Waste reduction techniques.* Minimizing 'flash' and scrap is critical for profitability and sustainability. Modern resin formulations are paired with advanced processing technologies to reduce waste.[36]
   - *Hot runner systems.* Unlike cold runner systems that produce waste that must be discarded, or re-processed, hot runners keep the plastic molten, significantly reducing waste in injection molding.
   - *Simulation and tooling.* Using AI-powered mold flow analysis, engineers can predict and prevent defects like flash or short shots before manufacturing the mold.
   - *Process optimization.* Adjusting injection speed and pressure using 'Scientific Molding' techniques reduces flash and ensures consistent quality.

[35] More arguments at https://www.technh.com/blog/metal-to-plastic-conversion-benefits-of-plastic-injection-molding-with-technh/

[36] More details at https://www.chinaruicheng.com/news/best-practices-to-reduce-material-waste-in-injection-molding-optimize-production/ and https://eureka.patsnap.com/report-how-to-minimize-resin-wastage-in-transfer-molding

- *Material recycling.* Incorporating regrind (recycled plastic scrap) directly into production lines (regrind programs) is a standard practice to reduce raw material waste.

3. *Economic impact and ROI.* Switching to more expensive, high-performance, or sustainable modern plastics often results in a better long-term ROI (Radu et al., 2025; Liu, 2025; Kutty & Mullungal, 2026).
   - *Reduced total cost of ownership.* Although the upfront cost of advanced resin may be higher, plastic parts often reduce total production costs by 25–50% by eliminating secondary operations like machining, painting, or coating.
   - *Functional integration.* Modern plastics allow for complex geometries that consolidate multiple metal components into a single injection-molded part, reducing assembly labour and fastener costs.
   - *Durability and lower maintenance.* Engineered plastics resist corrosion and fatigue better than metals, leading to longer operational life and lower replacement costs.
   - *Logistics savings.* Lower density plastics reduce shipping and freight costs, improving the financial picture throughout the product's life.

4. *LCA Methodologies (in brief).* Engineers use Life Cycle Assessment (LCA) to quantify the environmental impacts from raw material extraction ('cradle') to disposal or recycling ('grave') (Cao, 2017; Sabate & Kendall, 2024; Mousania & Atkinson, 2025).
   - *ISO 14040/14044 Standards.* These provide the framework for impact assessment, including the four stages: Goal and Scope definition, Inventory Analysis, Impact Assessment, and Interpretation.
   - *Process-Based vs. Hybrid Models.* Process-based LCA is often used for high-accuracy analysis, though hybrid models (combining detailed process analysis with economic data) are increasingly popular for complex, modern material chains.
   - *Key Environmental Trade-offs.* While plastic recycling is growing, LCAS often show that the manufacturing of certain polymers (like PA6) can have high greenhouse gas impacts compared to lighter materials like PET, requiring careful material selection based on the specific application.

Enhancing Throughput via Material Properties

New plastic formulations and advanced additives are designed to optimize high-volume manufacturing by specifically addressing the most time-consuming phases of injection molding. Several aspects are encountered in this area.[37]

1. *Fast-crystallizing polymers and additives.* Modern resins and additive packages, such as nucleating agents, accelerate the solidification process within the mold, allowing for significantly reduced cycle times. Important actions could take into consideration the following aspects (Schäfer et al., 2019; Tatara, 2024):
   - *Cooling time reduction.* The integration of specialized nucleants, such as colloidal silica or advanced mineral-organic hybrids, can enhance the crystallization rate, allowing for a 20–30% reduction in the cooling phase, particularly in materials like PP, Nylon, PBT, and ABS.
   - *Faster ejection.* By speeding up crystallization, the polymer reaches structural integrity sooner, enabling earlier ejection and increasing total production rates by up to 12% in packaging applications.
   - *Bio-based alternatives.* Nucleating agents like kraft lignin have been shown to reduce the cycle time of PLA (a typically slow-crystallizing material) by improving crystal formation, facilitating faster demolding.
2. *Low-friction additives.* Integrating internal lubricants directly into the polymer matrix eliminates the need for external, spray-on release agents, leading to faster, more automated, and cleaner production (Rajak et al., 2021; Kumar, 2025)
   - *Material release.* Additives such as PTFE (polytetrafluoroethylene) or molybdenum disulfide (MoS_2) create a non-stick surface, improving part release from complex molds.
   - *Maintenance reduction.* Because these additives reduce surface adhesion, they lower the frequency of cleaning molding machines, decreasing downtime for maintenance.
   - *Wear resistance.* These additives also enhance surface durabil-

[37] More details at https://www.tedesolutions.pl/en/blog/production-cycle-optimization-injection; practical information at https://www.plasticstoday.com/packaging/plastic-additives-said-to-lower-pharma-packaging-cycle-times-up-to-12-

ity and wear resistance, allowing for longer mold lifespan and more consistent part quality.

3. *Energy-efficient processing.* 'New Approach' plastics are engineered to reduce the energy footprint of the molding process through enhanced flow characteristics (Tatara, 2024; Kumar, 2025).
   - *Lower processing temperatures/pressures.* Many new resins or compounds have lower melting points, which allows manufacturers to reduce machine temperatures and clamping pressures.
   - *Shear-thinning properties.* Enhanced shear-thinning behaviour ensures that the material flows more easily under high shear, reducing the required injection pressure and decreasing energy consumption.
   - *Innovative processing methods.* Techniques like baroplastics leverage low-temperature, high-pressure processing to create sustainable products with significantly lower energy inputs, reducing CO_2 emissions.

These advances enable manufacturers to decrease cycle times by up to 30% without sacrificing part quality, translating to substantial annual savings in machine hours and energy costs.

Life Cycle Assessment (LCA) Framework (Brief Overview)

Life Cycle Assessment (LCA) is a crucial framework for industrial engineers to move beyond simple cost-per-kilogram calculations and assess the total environmental impact of a plastic component across its entire lifespan, typically adhering to the *ISO 14040/44 standards.* An LCA for a plastic component generally covers these four key stages as presented in the following (Cao, 2017; Sabate & Kendall, 2024; Mousania & Atkinson, 2025; Kaynak et al., 2025; Mudersbach et al., 2025).

1. *Raw material extraction.* This stage analyses the 'cradle-to-gate' impact, comparing the carbon cost and environmental burdens of *Virgin Petro-plastics* (fossil fuel-based) against *Bio-based Feedstocks* (e.g., corn, sugarcane, algae).[38]
   - *Key consideration.* While bio-based plastics can reduce fossil

[38] More practical information at https://earthshiftglobal.com/the-complex-story-of-biobased-plastics-in-lca

dependence, they may have higher impacts in areas like eutrophication and toxicity.
- *Carbon footprint.* Bio-based materials often show lower Global Warming Potential (GWP) due to carbon uptake (sequestration) during plant growth.

2. *Manufacturing impact.* This stage measures the energy and resources utilized in converting raw plastic granules into a finished product, including injection molding, extrusion, or 3D printing (Mannheim, 2021).
   - *Energy drivers.* The energy used for heating, cooling, and operating machinery (injection molding) is a major contributor to this stage's LCA.
   - *Process comparison.* Studies show that injection molding typically has lower environmental impacts compared to 3D printing (Additive Manufacturing) for large batch production, as 3D printing often consumes more energy per part, though it allows for less material waste.

3. *Use phase.* This phase calculates the environmental impacts (or savings) created while the part is in service. A common example is the lightweighting of vehicles, where plastic parts replace heavier metal counterparts (Gonçalves et al., 2022; Freire et al., 2025; Perera et al., 2025)
   - *Fuel savings.* A lighter plastic component (e.g., in a car dashboard, bumper, or interior trim) saves fuel (or electricity in EVS) over 100,000 miles, directly reducing the lifetime CO_2 emissions of the vehicle.
   - *Impact dominance.* In automotive applications, the use phase often dominates the total LCA, accounting for 26%–96% of the full life cycle impacts.

4. *End-of-Life (EOL) and circular potential.* This stage evaluates the environmental consequences of the part's disposal, aiming for a 'cradle-to-cradle' approach (Mannheim, 2021).
   - *Mechanical recycling.* Re-melting and reusing thermoplastics (e.g., PET, PP) is generally preferred to minimize impacts.
   - *Chemical recycling.* Evaluating advanced methods like pyrolysis to break down mixed or contaminated plastics into chemical feedstocks.
   - *Industrial composting.* An option for bio-based, biodegradable

TABLE 3.7 A Comparison on Some Metrics in the Case of Traditional and New Plastic Approaches

Metric	Traditional Metal Approach	New Plastic Approach
Tooling Cost	High (multi-stage dies)	Moderate (Single-cavity high-speed molds)
Energy per Part	Very High (Smelting/Machining)	Lower (Thermal Processing)
Secondary Ops	Deburring, Polishing, Painting	Often 'Net-Shape' (No finishing needed)
Logistics Cost	High (Heavy)	Low (Lightweight)

plastics (e.g., PLA), provided the waste is managed in specialized facilities.

Key takeaway. By analysing these four stages, industrial engineers can identify 'hotspots,' the most environmentally damaging parts of the life cycle, and make informed decisions that reduce overall ecological impact.[39]

Economic Impact: The Total Cost of Ownership (TCO)

While advanced polymers like PEEK or bio-polyamides have a higher purchase price than steel or commodity PP, their TCO is often lower due to: (a) *part consolidation* (one complex plastic molding can replace an assembly of five metal parts, reducing assembly labour and inventory management); (b) *corrosion resistance* (eliminating the need for expensive anti-rust coatings, painting, or galvanization) and (c) *weight savings* (in logistics and aerospace, every gram saved translates to lower transport costs and higher payload capacities) (Table 3.7).

Advanced polymers like PEEK (polyetheretherketone) and bio-polyamides offer a lower Total Cost of Ownership (TCO) compared to traditional materials like steel or commodity PP, despite a higher initial purchase price. This is achieved through significant savings in manufacturing, maintenance, and operational efficiency. Key factors contributing to this reduced TCO include (Efimov & Haragâş, 2025):[40]

[39] More practical aspects at https://carbontrail.net/blog/life-cycle-assessment-stages-the-four-stages-of-lca/

[40] More arguments at https://aipprecision.com/5-advantages-of-peek-versus-metals/; more practical implications at: https://specialty-polymer.com/is-peek-stronger-than-steel-aluminum-or-titanium/

- *Part consolidation.* Advanced polymers facilitate injection molding of complex geometries, allowing a single component to replace multiple metal parts (e.g., an assembly of five or more). This reduces assembly labour, inventory management costs, and the need for fasteners.
- *Corrosion resistance.* PEEK and other high-performance polymers are inherently corrosion-resistant and chemically inert, eliminating the need for expensive anti-rust coatings, surface treatments, or galvanization, which are necessary for steel, particularly in harsh environments.
- *Weight savings.* These polymers are significantly lighter than traditional metals, for example, PEEK is roughly 1/5 to 1/6 the density of steel or stainless steel. In industries such as aerospace and logistics, this reduces fuel consumption and operational costs, while allowing for higher payload capacities.
- *Reduced maintenance and longevity.* Due to high wear resistance and durability, components made from these polymers last longer, leading to fewer replacements and less downtime.
- *Improved efficiency (logistics).* The reduced weight of parts improves energy efficiency and reduces transportation-related costs over the product's lifespan.

While PEEK can cost 20 to 30 times more than some metals per unit, its ability to outperform metal in high-stress applications makes it a more cost-effective solution when considering the total, long-term system cost. Furthermore, the 'New Approach' minimizes industrial scrap through:

- *Regrind integration.* Advanced sensors in modern molding machines allow for the immediate re-integration of 'runners' and 'sprue' (waste plastic) back into the production line without losing mechanical properties.
- *Zero-waste additive manufacturing.* Unlike subtractive CNC machining, which turns up to 70% of a metal block into 'chips,' 3D printing uses only the material required for the part.

Authors' Note. The debate presented in this sub-chapter, on the actual knowledge inventory proves that sustainability is not just an ethical 'add-on,' it is a core component of *process optimization.* A more sus-

tainable material often leads to a leaner, more profitable production line.

Future Trends and Conclusion

In this sub-chapter will be discussed aspects related to *nanocomposites* (the potential of graphene-infused plastics); *policy and ethics regarding* the role of industrial engineers in solving the global plastic waste crisis and a *final synthesis will try to answer the question:* How material science is becoming a core pillar of industrial systems design?

As we look toward the 2030s, the 'New Plastic Materials' (NPMS) approach is evolving from simple material substitution to the creation of *autonomous, biological-synthetic hybrid systems.* This final section outlines the frontiers of industrial plastic research and summarizes the sub-chapter's core thesis.

Nanocomposites: The Graphene Revolution

The integration of nanotechnology is the next frontier for industrial plastics. By infusing polymers with nanoscale fillers, we achieve properties previously thought impossible:

- *Ultra-high strength.* Graphene-reinforced polymers are approaching the tensile strength of high-grade carbon steels while remaining significantly lighter.
- *Thermal management.* New plastics are being engineered with directional thermal conductivity, allowing them to act as 'heat pipes' in high-density electronics without the need for copper fins.
- *Gas barrier properties.* Nanoclays are being used to create 'impenetrable' plastics for hydrogen storage and high-vacuum industrial applications.

Bio-Hybrid and Living Materials

Moving beyond 'bio-based,' the future lies in *Living Materials.* Researchers are experimenting with embedding dormant bacteria or fungi within plastic matrices:

- *Self-cleaning surfaces.* Bacteria that activate in the presence of contaminants to 'eat' biofilms off industrial equipment.
- *CO_2-consuming plastics.* Polymers that continue to sequester carbon from the factory air throughout their operational lifespan.

TABLE 3.8 The Future Outlook (2026–2035)

Trend	Technology	Impact on Industrial Engineering
Material intelligence	AI and Machine Learning	Rapid deployment of 'Hyper-Specific' resins
Molecular circularity	Chemical Recycling (Monomer Recovery)	Infinite recycling without loss of quality
Active systems	4D Printing and Shape Memory	Reduction in mechanical actuators and motors
Carbon sovereignty	Direct Air Capture (DAC) Feedstocks	Moving from 'Carbon-Neutral' to 'Carbon-Negative'

Polymer Informatics and AI-Driven Discovery

The traditional 'trial and error' method of discovering new plastic blends is being replaced by *material informatics:*

- *High-throughput virtual screening.* AI models predict the properties of millions of polymer combinations in seconds.
- *Autonomous material synthesis.* Robotic labs synthesize and test new plastic formulations overnight, accelerating the development of application-specific resins from years to weeks.

Conclusion: The New Industrial Materiality

The integration of NPMS in industrial engineering is no longer a matter of cost-cutting; it is a *strategic necessity.*

- *Synthesis of performance and planet.* The modern engineer must balance the 'Mechanical Trinity' (Strength, Weight and Durability) with the 'Environmental Trinity' (Circularity, Carbon Footprint and Toxicity).
- *The paradigm shift.* We are moving away from a world of 'standard materials' toward a world of *bespoke polymers,* where every gear, seal, and housing is chemically tuned for its specific industrial role.

In synthesis, Table 3.8 presents the synthesis of the future trends in NPMS.

Final thought. The industrial engineers of the future will not just select materials from a catalogue; they will define the molecular properties required for their systems, effectively becoming *architects of matter.*

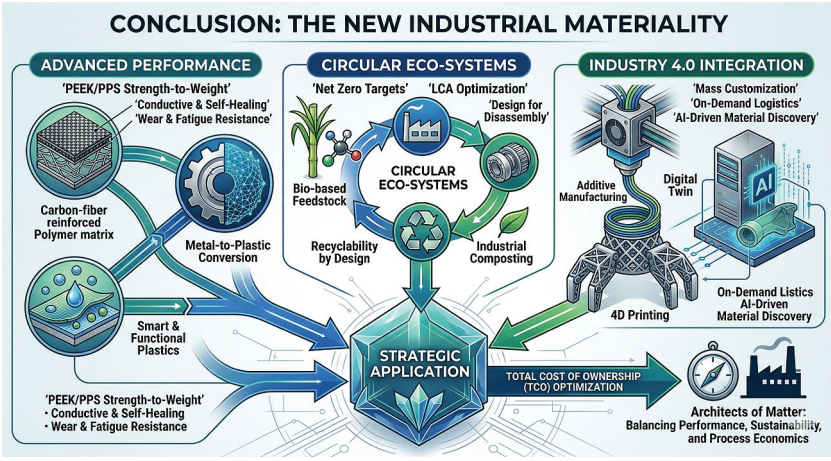


FIGURE 3.10 The New Industrial Materiality

NOTES Generated with Gemini Application, based on chapter's development.

Based on the structure provided, Figure 3.10 presents a detailed breakdown of the conclusions related to the NPMS, analysing how it visually synthesizes the chapter's core themes. This comprehensive infographic serves as the visual abstract for the entire chapter. It is designed as a dynamic, interconnected system where three primary industrial drivers (Performance, Sustainability, and Process) converge at a central hub of 'Strategic Application.' Also, the diagram should be read and understand as a flow from the three outer modules toward the center, and then to the final strategic outcomes at the bottom-right.

Module 1: Advanced performance (synthesizing the secont and the fourth section). This module, located at the top-left, represents the physical and chemical engineering aspect of New Plastic Materials (NPMS). It visually integrates the high-stress requirements of industrial engineering with the novel capabilities of smart plastics.

- *Materials at the apex.* The icon of the carbon-fibre reinforced lattice represents the material science discussed in the second section. The text 'PEEK/PPS Strength-to-Weight' directly references the high-performance polymers that are replacing metal.
- *The Conversion process.* The cog-wheel merging into a digital network (labelled Metal-to-Plastic Conversion) visually captures the core engineering task of redefining parts for polymer-specific geometry.

- *The Smart layer.* The icon for Smart and Functional Plastics (showing layered materials responding to stimuli) synthesizes the fourth section, specifically the self-lubricating, conductive, and self-healing properties that reduce maintenance downtime.

Module 2: Circular Eco-Systems (Synthesizing the third and the sixth section). Located at the top-centre, this module addresses the mandate for industrial sustainability. It moves beyond 'greenwashing' to present a quantifiable, closed-loop approach.

- *The Feedstock shift.* The visual of the plant stalk (labelled Bio-based Feedstock) represents the shift from fossil fuels to renewable sources like PLA and PHAS discussed in the third section.
- *The LCA loop.* The central green recycling symbol, surrounded by 'Net Zero Targets' and 'LCA Optimization,' visualizes the process optimization framework discussed in the sixth section. It connects the factory output (Industrial Composting) back to the material design stage (Design for Disassembly).
- *Engineering metric.* The flow arrow leading directly from this module to the central hub demonstrates that 'circularity' is now a non-negotiable input for industrial application.

Module 3: Industry 4.0 Integration (synthesizing the fifth section). Located at the top-right, this module showcases the *digital execution* of NPMS. It represents how new materials enable new manufacturing paradigms.

- *On-demand production.* The visual of the 3D printer creating a complex lattice structure (labelled Additive Manufacturing and 4D Printing) represents the 'Point-of-Need' production model from the fifth section, utilized for custom fixtures and temporary tooling.
- *Digital material discovery.* The integration of the AI server (AI and Digital Twin) highlights the role of material informatics in accelerating the R&D of bespoke polymers, making manufacturing On-Demand and efficient.

Convergence: Strategic application and outcomes (synthesizing the sixth and the seventh section). All three modules flow into the central hub, labelled *Strategic Application.* This is the synthesis point of the

chapter: a material is only 'new' if it is applied strategically to solve a system-level industrial problem.

- *Primary economic outcome.* The flow proceeds directly to Total Cost of Ownership (TCO) Optimization. This arrow proves the financial argument from the sixth section that NPMS reduce the long-term, cradle-to-grave expenses.
- *The future role.* The figure concludes with a final compass and factory icon, labelled 'Architects of Matter.' This visually summarizes the chapter's conclusion (the seventh section): the future industrial engineer must balance Performance, Sustainability, and Process Economics as interconnected disciplines.

The Vision for a Plastic Waste Prevention and Management

Plastic has become one of the most important materials in the contemporary economy, but its high versatility has produced an evident side effect; the production and management of plastic waste clearly show how far the current system still is from a truly circular model. At the global scale, the OECD estimates that in 2019 plastic production reached 460 million tonnes and that plastic waste generated amounted to 353 million tonnes; of this, only 9% was effectively recycled, 19% was incinerated, almost 50% was landfilled, and the remaining 22% was mismanaged or dispersed into the environment (OECD, 2022a, 2022b).

In Europe the picture appears less critical than the global average, but it is still far from full circularity. According to Plastics Europe, in 2022, 32.3 million tonnes of post-consumer plastic waste were collected in the EU27+3 area; of this, 26.9% was sent to recycling, 49.6% to energy recovery, and 23.5% to landfill (Plastics Europe, 2024). These data, however, describe the destination of the waste collected and treated, not the actual recycling rate of the whole system. In fact, the Joint Research Centre (JRC) of the European Commission points out that, when losses and inefficiencies along the value chain are considered, the average 'end-of-life' recycling rate in the EU-27 stands at 19.6%, even though 36.6 Mt of waste are properly collected, because a significant share of the materials is still lost or managed inefficiently before final recycling (Amadei & Ardente, 2025). For Italy, the most homogeneous and up-to-date data mainly concern packaging: Eurostat indicates that in 2023 the country recycled 49% of plastic packaging (Eurostat, 2025), as also confirmed by the *Recycling in Italy 2024* report (Fondazione per lo

Sviluppo Sostenibile, 2024), which reports a 48% recycling rate for plastic packaging in 2023. Literature research estimated referring to total Italian plastic waste about 4.8 million tonnes, of which 31.4% were sent to recycling, 32.8% to energy recovery, and 35.8% to landfill (Preka et al., 2022).

These numbers suggest that the problem is not only the quantity of plastic produced, but also how it is designed, used, and above all how it is managed when it becomes waste. The most realistic vision, therefore, is not that of a rapid elimination of plastic production, but that of a drastic reduction in avoidable uses, coupled by a strong growth in the capacity to intercept, sort, and recycle the flows that will inevitably continue to exist (OECD, 2022a, 2022b).

Prevention of Plastic Waste Generation

Prevention of plastic waste generation is the first level of intervention and consists in reducing waste before it is even generated. In Europe this priority mainly concerns packaging, which accounts for about 40% of the plastic used and represents a very significant share of waste and marine litter; for this reason, prevention cannot be limited to replacing one material with another, but must also aim to reduce superfluous uses, simplify packaging, and promote reuse and refill systems (European Commission, 2026a, 2026b; UNEP, 2021).

From a regulatory point of view, the European Single-Use Plastics Directive aims to reduce the impact of the most problematic single-use products, particularly those dispersed in the marine environment (European Commission, 2026a, 2026b). Alongside it is the new Packaging and Packaging Waste Regulation (PPWR), in force since 11 February 2025 and applicable from 12 August 2026, which aims to reduce the quantity of packaging, make it recyclable by 2030, and also encourage reuse models and the use of customers' own containers in takeaway systems (European Commission, 2026a, 2026b). However, the literature shows that taxes, bans, and obligations really work only when practical alternatives and effective controls exist (Cornago et al., 2021; Adeyanju et al., 2021). Bulk, refill, and reusable systems can also reduce waste at source, but they are not automatically better in every context. Life cycle assessments show that their benefits depend on the actual number of reuses, transport distances, washing, and the efficiency of the return system (Espinoza-Orias & Lundquist, 2025; De Jong et al., 2025).

Lastly, a central role belongs to eco-design, that is, the design of sim-

pler, reusable, and recyclable products and packaging, and to extended producer responsibility (EPR), which can push companies to reduce upstream the quantity and complexity of the plastic placed on the market (Zhu et al., 2022; OECD, 2024). To sum up, effective prevention arises from the integration of rules, design, reuse models, and changes in consumption habits, while information campaigns alone have limited effects if they are not coupled by structural measures (Mathew et al., 2023).

Plastic Waste Management and Technological Innovations

Once waste exists, the priority becomes preventing its dispersion and channeling it into recycling flows. A point that is often underestimated emerges: efficient recycling cannot exist without good collection, which is implemented through simple rules, adequate infrastructure, and coherent incentives. Given the quantity of waste produced, end-of-life management plays a fundamental role in addition to prevention.

In already developed countries, the greatest margins for improvement lie in the quality of collection rather than in its mere existence. The combination of widespread separate collection, door-to-door systems, controlled-access bins, pay-as-you-throw schemes, and deposit systems for specific streams can increase both the quantity and, above all, the purity of the material collected. The European Environment Agency (EEA) underlines that pay-as-you-throw systems work precisely because they transfer to the waste producer an economic signal proportional to the unsorted waste generated, while a recent review on deposit return schemes shows that the best results are observed when the deposit is sufficiently high, return points are widespread, and public communication is clear. For streams such as beverage bottles, therefore, it makes sense to think of dedicated, high-quality collection systems; for other streams, the priority remains making ordinary separate collection more efficient (EEA, 2023; Picuno et al., 2025).

In developing countries, on the other hand, the issue is more radical: in many areas the problem is not optimizing an existing system but building a minimal and reliable one. Ferronato et al. show that in many low- and middle-income cities open dumping and open burning remain widespread practices, and that the most effective actions are often pragmatic ones: simplified collection systems, small sorting centers, awareness campaigns, and cooperation among local authori-

ties, universities, NGOS, and companies. Even more important is the role of the informal sector. Velis and Cook also argue that integrating and strengthening waste collection operators may represent the fastest and least costly way to increase collection and reduce leakage, provided this happens under safer conditions and with less precarious remuneration. However, it is worth avoiding an oversimplified reading: it is true that poor waste management often reflects deeper socioeconomic problems, such as rapid urbanization, overcrowding, lack of services, and institutional weakness; but it is also true that leaving it unresolved further worsens public health, urban flooding, environmental degradation, and poverty (Ferronato et al., 2024; Velis & Cook, 2022).

Recycling plants are the industrial link that turns waste into a resource, but their effectiveness depends on everything that happens before: collection, quality of input, sorting technologies, and product design. For this reason, today we speak less and less of a 'plant' in an isolated sense and more and more of a 'value chain.' When the plastic arrives dirty, composite, additivated in incompatible ways, or mixed without criteria, even the best technology performs poorly (Lubongo et al., 2024).

Mechanical recycling remains today the most established route. In simple terms, it consists of sorting the material by compatible polymers, washing it, shredding it, remelting it, and extruding it into new pellets or semi-finished products. Its main strength is that it is the most industrially mature and widespread technology and, in most of the comparisons available, the one that shows the best economic and environmental results while maintaining an acceptable quality of recycled products. The quality of the output depends greatly on the quality of the input stream, and thermo-mechanical degradation, contamination, and the presence of multilayers or complex additives strongly limit the quality of the recyclate output (Uekert et al., 2023).

The margins for improvement are nonetheless wide. Today the most promising innovation concerns not only extrusion, but the entire waste preparation phase: optical sensors, NIR spectroscopy, machine learning, and robotic systems are increasing the precision and productivity of sorting; at the same time, work is being done on stabilizers, compatibilizers, delamination of multilayers, removal of labels, inks, and contaminants, as well as upstream design-for-recycling. Mechanical recycling is the first choice for homogeneous and clean streams but, despite technical improvements, it cannot on its own absorb all the complexity

of contemporary post-consumer plastic (Lubongo et al., 2024; Uekert et al., 2023; RecyClass, 2026).

Chemical recycling refers to a family of technologies that are very different from one another. Some, such as depolymerization or solvolysis, aim to bring certain polymers back to their original monomers; others, such as pyrolysis and gasification, convert plastic waste into oils, gases, or chemical intermediates to be reintroduced into basic chemistry. Luo et al. clearly distinguish these three major strands and underlines that their usefulness depends on the type of polymer and the desired final product. The main advantage of chemical recycling is that it can treat streams that mechanical recycling digests poorly: dirtier mixtures, multilayer plastics, materials with severe degradation, or materials with very high final quality requirements (Luo et al., 2024).

In any case, mechanical recycling is not without critical issues. The JRC has highlighted that these technologies are promising as a complement to mechanical recycling, but that their environmental and economic performance depends strongly on input purity, yields, energy consumption, by-product management, and the destination of the outputs. In parallel, the most recent reviews insist on a common-sense point: chemical recycling makes sense above all when it avoids incineration or landfilling of streams that would otherwise be difficult to recover, not when it diverts good-quality material away from mechanical recycling. In other words, it should not replace the existing hierarchy but close the 'gap' that mechanical recycling leaves open (Garcia-Gutierrez et al., 2023; Alabi et al., 2025; Jiao et al., 2024).

The most interesting innovations concern not only waste treatment, but the entire life cycle of plastic. A first advantage is that of alternative feedstocks: recycled plastic, biomass, bio-based resources, and carbon from captured CO_2 can reduce dependence on oil and gas, but they are not automatically more sustainable in every case. The JRC insists that these alternatives should be assessed using harmonized Life Cycle Assessment (LCA) criteria, because the benefits depend on the type of raw material, the final uses, transport, end-of-life, and any biodegradability or compostability properties. This last point is important, since public communication still tends to use labels such as 'bio-based,' 'compostable,' and 'biodegradable' as if they were sufficient on their own to guarantee sustainability (Nessi et al., 2021).

A second front is the digitization of sorting and recycling systems. Reviews on AI and sorting show that spectroscopy, machine learning,

artificial vision, and robotics are already improving polymer identification, reducing contamination, and increasing plant productivity. This progress is crucial, because one of the European-level 'bottlenecks' is not only how much waste is collected, but how much of that waste can then be brought to quality specifications useful for recycling into high-value applications. Looking ahead, AI can also help optimize more advanced processes, including thermochemical and biological ones (Lubongo et al., 2024; Fang et al., 2025).

A third front concerns biological and enzymatic recycling, today mainly for PET. The most recent reviews describe the enzymatic approach as promising because it operates under milder conditions and with lower energy demand than several traditional chemical routes; at the same time, however, problems of industrial scale, productivity, pretreatment, and enzyme cost remain open. For this reason, at least in the near future, it is more correct to consider it a high-potential emerging technology rather than a mature solution. The same caution applies to many other innovations: solvent-based purification, advanced compatibilizers, mixed-waste sorting, and product redesign can make a difference, but only if they are integrated into a coherent industrial strategy and not treated as standalone technologies (Sun et al., 2024; Alabi et al., 2025; Zhu et al., 2022).

Final Considerations

The properties of plastic (light weight, low cost, resistance, versatility) explain why it will be difficult to replace it entirely in the short term. A credible vision, therefore, cannot be limited to generically invoking scenarios with 'less plastic,' but must distinguish between avoidable uses and uses that are still difficult to replace. Reducing waste generation remains essential, especially for unnecessary single-use applications; but the decisive point, in the short and medium term, is the quality of end-of-life management. From this point of view, the priorities are fairly clear. First: intercept as much of the waste stream as possible, reducing dispersion into the environment to a minimum. Second: increase the share of material that reaches sorting and recycling facilities under conditions compatible with value recovery. Third: use mechanical recycling as the backbone of circularity and chemical recycling as a complementary technology for the more difficult fractions. Fourth: limit the use of energy recovery to residual streams that cannot otherwise be valorized; the LCA literature continues to consider scenarios

based almost exclusively on incineration to be unfavorable (Uekert et al., 2023; Garcia-Gutierrez et al., 2023; Jiao et al., 2024).

As regards a reasonably achievable recycling percentage, in the European context for plastic packaging, 50–55% in the near future appears to be a credible target since it coincides with EU targets and some countries such as Italy are already close to these values (48% in 2023 according to *Recycling in Italy 2024*), while the EU as a whole reached 42.1% in 2023 for plastic packaging alone. For all post-consumer plastic, however, the target is more difficult: starting from the European 26.9% in 2022, growth towards values in the order of 35–40% in the most advanced systems can be considered realistic only if high-quality collection, sorting, and industrial outlets for recyclate increase significantly. From a fully circular perspective, the optimal objective would be to go beyond that, but it is unlikely to achieve complete circularity; there will in any case be residual contaminated, composite, or degraded shares. In this perspective, perhaps the most useful reference is the OECD 'Global Ambition' scenario, which sees almost 60% of global plastic waste recycled by 2060: not a certain forecast, but an indication of the scale of transformation required (OECD, 2022b).

Finally, in developing countries poor plastic waste management should not be read as a marginal issue or as one separate from social problems; it is often a direct consequence of them, and precisely for this reason it cannot be postponed. If collection does not exist, if settlements grow faster than services, if the informal sector is not recognized, and if uncontrolled dumping remains the norm, plastic (and waste more generally) becomes an amplifier of environmental and health vulnerability. The true vision for plastic waste prevention and management, then, is not a single formula valid everywhere; it is a differentiated strategy, which in wealthy contexts must aim at quality, circularity, and the reduction of incineration and landfill, and in fragile contexts must start from building minimal, inclusive, and stable services, capable first and foremost of stopping the dispersion of waste into the environment.

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Chapter Four

Innovative Digital Tools and E-Learning for Green Skills Development

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https://doi.org/10.53615/978-83-65020-56-7/147-184

The E-Learning Classroom and MOOCs: Pedagogical Approaches to Circular Economy and Plastic Waste Management

The transition towards a circular economy (CE) and sustainable plastic waste management is a critical global challenge, increasingly addressed through education and capacity building. As digital transformation reshapes the educational landscape, the 'e-learning classroom' and Massive Open Online Courses (MOOCS) have emerged as pivotal tools for disseminating knowledge and fostering 'green skills' among diverse learners, from students to industry professionals (Školnik Škrabe et al., 2025). This review examines current pedagogical approaches in online education for circularity, with a particular focus on the EDU4PlastiCircular project and its contribution to the field.

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

Massive open online courses (MOOCS) emerged in the early 2010s as a disruptive innovation within higher education institutions, promising to democratize access to quality learning resources on an unprecedented scale. MOOCS are characterized by their openness (often free or low-cost), scalability (allowing thousands of simultaneous learners), and flexibility (allowing self-paced or cohort-based learning) (Arıker, 2021). Major platforms such as Coursera, edX, FutureLearn, as well as other local, regional initiatives have proliferated globally, offering courses in various disciplines. The COVID-19 pandemic has accelerated the adoption of MOOCS as educational institutions around the world have faced sudden closures and the imperative to move to distance learning (Agrawal & Ting, 2022). This crisis has revealed both the potential and the limitations of online education, catalysing innovations in pedagogical design, technological infrastructure, and learner support systems (Borowska & Kołodziej, 2022). In addition, MOOCS have been recognized as a fundamental tool for the delivery of entrepreneurial education, offering methods to reach large volumes of students in culturally rich virtual workspaces.

Recent developments have introduced hybrid models, including SPOCS (Small Private Online Courses) that combine MOOC technologies with limited enrolment and institutional integration, as well as blended learning approaches that blend online and face-to-face instruction. Thus, MOOC platforms have evolved from simple content repositories to sophisticated learning ecosystems that incorporate adaptive learning technologies, social learning features, and accreditation mechanisms (Arıker, 2021; Konecki, 2025).

The Role of E-Learning and MOOCS in Circular Economy Education

Online education offers a scalable and accessible platform for teaching the complex, interdisciplinary nature of the circular economy. Research indicates that MOOCS are particularly effective for lifelong learning and professional development in environmental management (Pérez & Spalletti, 2021). Modern e-learning for CE has moved beyond traditional didactic teaching towards more interactive and student-centred methodologies. Literature highlights key strategies such as:

- *Interdisciplinary integration.* Effective CE education must bridge the gap between technical, economic, social, and managerial perspectives (Wageningen University & Research, 2023).

- *Inquiry-based and simulation learning.* Studies comparing different teaching methods for plastic waste management found that 'guided inquiry' and 'gaming simulations' significantly outperform direct teaching in enhancing students' problem-solving capacities and recycling intentions (Yeung et al., 2017).
- *Visual didactic regulators.* The use of visual tools and digital libraries helps in structuring complex information about the plastic lifecycle, from design to end-of-life (Steinberg et al., 2025).

Content analysis of existing online courses reveals a shift from simple waste management (downstream solutions) to a holistic 'lifecycle approach' (upstream and downstream). Courses are increasingly emphasizing sustainable design, circular business models, and the reduction of microplastics (Dermol & Dermol, 2024). For instance, the 'Sustainable Packaging in a Circular Economy' MOOC by Delft University of Technology focuses on design strategies to eliminate waste before it is created.[1]

Circular Economy and Plastic Waste Management in Higher Education

Plastic systems involve interconnected processes of production, consumption, waste management, and environmental leakage, thus the plastic waste management as a complex, multi-scalar system problem. The implementation of the circular economy (CE) framework proposing the close of the material loops through reuse, recycling, and redesign of products and systems is constrained by behavioral, institutional, and knowledge-related barriers (Kirchherr et al., 2017). Consequently, education in this domain must address not only technical processes but also decision-making, responsibility, and systemic interactions.

The framework for Education for Sustainable Development developed by UNESCO emphasizes competencies such as critical thinking, collaboration, and strategic action (UNESCO, 2017). Research indicates that effective ESD requires participatory and action-oriented learning (Lozano et al., 2017). Thus, learning is extended beyond knowledge acquisition toward competence development and action.

[1] See https://www.edx.org/learn/circular-economy/delft-university-of-technology-sustainable-packaging-in-a-circular-economy

In this context, Higher Education Institutions (HEIS) serve as 'microcosms' for the circular transition. Integrating CE principles into university curricula involves not only theoretical knowledge but also practical 'campus-as-a-living-lab' initiatives where students manage plastic waste on-site (Vergani, 2024). The concept of 'green skills' is central to modern sustainability pedagogy. These skills encompass technical expertise (e.g., polymer recycling), cognitive skills (e.g., systems thinking), and values/attitudes necessary for a climate-neutral economy (United Nations Environment Programme, 2025). The EDU4 PlastiCircular project specifically targets these skills to bridge the educational gap in plastic circularity (Školnik Škrabe et al., 2025).

The EDU4 PlastiCircular Project: A Case Study in Innovative Pedagogy

The Erasmus+ project EDU4 PlastiCircular (Education for Plastic in a Circular and Climate Neutral Economy) represents a significant advancement in e-learning for plastic management.

- *Targeted training.* The project develops open-access training materials and an e-learning platform specifically designed for HEI staff, students, and industry managers (Školnik Škrabe et al., 2025).
- *Innovative methods.* By employing MOOCS and a digital library, the project promotes equitable access to high-quality education regardless of geographic limitations, as mentioned in the *Handbook for Trainers.*[2]
- *Curriculum structure.* The project's handbook for trainers outlines a structured approach with five chapters, covering the entire plastic value chain and emphasizing the transition to a circular and climate-neutral model (Giurea et al., 2025).

The EDU4 PlastiCircular Learning Ecosystem

The EDU4 PlastiCircular initiative can be analyzed as a learning ecosystem rather than as a single online course because its instructional architecture combines multiple actors, learning environments, resources, and activity types into an integrated system organized around a shared sustainability problem: plastic circularity and plastic waste management.

[2] See https://dermol.si/wp-content/uploads/2025/05/D2.3-Handbook-for-Trainers.pdf

In ecosystem terms, the relevant analytical units are not limited to content modules, but include the relationships among digital infrastructure, pedagogical design, learners, educators, project partners, and real-world contexts of application. This interpretation is consistent with design-based views of higher education, according to which technology-mediated learning environments become educationally effective when tools, tasks, and feedback processes are intentionally aligned with learning goals and participation structures (Laurillard, 2012). It is also consistent with the literature on Education for Sustainable Development, which emphasizes that sustainability competencies are best developed in settings that connect knowledge, action, and stakeholder interaction rather than in isolated disciplinary instruction (UNESCO, 2017; Wiek et al., 2011).

At structural level, the EDU4 PlastiCircular learning ecosystem consists at least of five components, described in Figure 4.1: content, pedagogical frameworks, social interaction, experiential environment.

The content is organized into thematic modules covering plastic materials, waste management, circular economy, organizational responsibility, and awareness and responsible behavior. Each module contains topics structured in lessons. The EDU4 PlastiCircular Handbook[3] provides the topics structured in Learning Activities and Assessment (LAA) as the fundamental instructional units that operationalize the course design. They are not single tasks, but structured methodological sequences that integrate learning objectives, instructional input, learner activity, and assessment.

The pedagogical design of EDU4 PlastiCircular reflects an integrated approach, combining experiential learning (experiments, internships), problem-based learning (case studies, design challenges), project-based learning (such as 3D printing), systems thinking (LCA, pathway mapping), collaborative learning (role-play, group projects), transformative learning (thorough reflection, ethical analysis). This integration supports the sustainability education which requires multi-method pedagogical frameworks to address complex, interdisciplinary problems and to support behavioral change. Importantly, these approaches are not applied independently but are embedded within the LAA structure, ensuring that each learning sequence combines conceptual understanding (through lectures, interactive lectures, e-learning platform

[3] See https://dermol.si/wp-content/uploads/2025/05/D2.3-Handbook-for-Trainers.pdf

readings, etc), active engagement of learners in activities in different learning environments, reflection on the new understanding, application in new contexts. This approach enables learners to move from knowledge acquisition to applied competence and action in the context of circular economy and plastic waste management.

The digital component is centered on an e-learning platform and digital resources that support access to materials, case studies, open educational resources, and online assessment. Among the multiple facilities and advantages of digitalization in the EDU4PlastiCircular learning ecosystem we mention in this context the access to the learning content, the opportunity for multiple interactions, the opportunities of learning analytics.

The social component is based on different types of interactions provided by the ecosystem: among learners, since many LAA propose collaborative activities (peer discussions, group production, or stakeholder simulations engaging methods like role-play, group projects, jigsaw), among authors (since the EDU4PlastiCircular learning ecosystem is the result of the collaboration of project members).

The ecosystem includes the experiential component, because learning sequences explicitly extend beyond the digital classroom to laboratory experimentation, field-like problem contexts, or workplace-based internship learning. In EDU4PlastiCircular, real-world integration is evident across modules, as for example: Plastic pollution pathway analysis (requires learners to map real environmental processes disturbed by plastics); Lifecycle assessment tasks (require evaluation of actual production and waste scenarios); Behavioral intervention design (requires learners to propose actionable strategies to reduce plastic use). These activities are not abstract exercises; they are structured to simulate or directly engage with real systems, enabling learners to connect knowledge with decision-making and intervention design.

The EDU4PlastiCircular learning ecosystem is addressed at different levels of educational activity (micro – individual, mezzo – course/classroom, macro – institutional), since it provides tools for a holistic design to link knowledge, skills and actions. The structure supports progression from cognitive to transformative outcomes, starting with knowledge and awareness, and analytical and systems thinking, going through ethical and systemic reasoning, and application and problem-solving, and envisaging behavioral and transformative outcomes. The transformative learning outcomes can be systematically developed

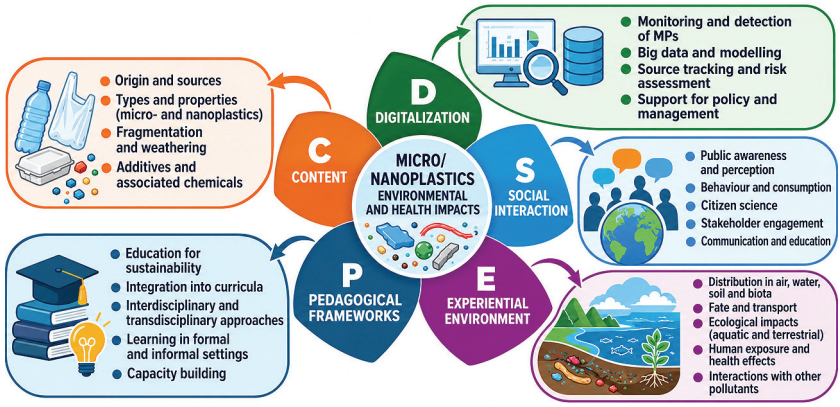


FIGURE 4.1 Components of the EDU4 PlastiCircular Learning Ecosystem

NOTES Created using ChatGPT.

through integration of cognitive, practical, and reflective activities, alignment of pedagogical approaches with competence frameworks, incorporation of real-world and behavioral dimensions. The combination of these elements enables learners to move from knowledge acquisition to systems understanding, competence development, behavioral change, perspective transformation. At the level of implementation, this concept can operate in various contexts, thus one can distinguish (design/implement) between different learning environments:

- *Digital learning ecosystem* – fully mediated by digital platform;
- *Blended ecosystem* – combines physical and digital environment;
- *Work-integrated ecosystem* – links academia with industry and practice;
- *Sustainable learning ecosystem* – focusing on complex, transdisciplinary challenges.

The EDU4 PlastiCircular learning ecosystem extends beyond the e-learning classroom by establishing a distributed learning ecosystem in which:

- Learning occurs across multiple contexts (digital, experiential, social);
- Stakeholders are integrated into the learning process;
- Real-world problems structure learning activities;

- Feedback supports iterative development;
- Behavioral and societal dimensions are explicitly addressed.

This configuration aligns with contemporary research in sustainability education, which identifies ecosystem-based approaches as necessary for developing competencies and enabling meaningful engagement with complex environmental challenges.

Challenges and Future Directions

Implementing sustainable, digital learning ecosystems faces structural, pedagogical, and technological challenges. Research in higher education indicates that sustainability education initiatives often encounter barriers related to institutional capacity, pedagogical integration, and digital transformation (Abo-Khalil, 2024). These challenges are not incidental but reflect the complexity of integrating interdisciplinary content, innovative pedagogies, and digital infrastructures within existing educational systems.

The EDU4PlastiCircular initiative provides a relevant case for examining these challenges, as it combines:

- Sustainability content (circular economy, plastic waste);
- Complex pedagogical approaches (experiential, problem-based, transformative learning);
- Digital mediation (e-learning platforms, learning analytics).

The *complexity of sustainability as a learning domain* is evident in:

- The need to connect material science with environmental systems;
- The integration of policy and responsibility with engineering design;
- The inclusion of behavioral and societal dimensions.

The challenge comes from the learners who may struggle to integrate interdisciplinary knowledge, to understand system-level interactions, to transfer knowledge across contexts.

To overcome these challenges, the EDU4PlastiCircular offers a modular structure with progressive complexity (from materials → systems → solutions → behavior) is necessary to scaffold learning.

The *pedagogical complexity* and instructional design demands due to the fact that each topic includes multiple LAAS combining lecture, activity, and assessment and activities vary from experiments to role-play, to design tasks requires high design effort for educators, need for pedagogical expertise to manage diverse methods, and difficulty in maintaining coherence across activities. To overcome the challenges due to pedagogical complexity, the use of a standardized LAA structure (learning objectives → activity → assessment) supports consistency and replicability. This reflects design-based approaches to teaching, where structured activity sequences improve alignment and clarity.

Digital transformation in higher education is associated with multiple barriers, including lack of infrastructure, insufficient digital competencies, and institutional constraints. Studies also highlight disparities in access to technology and digital skills as significant obstacles (Adhikari & Rana, 2024).

Although EDU4PlastiCircular is designed as an e-learning ecosystem, such challenges remain relevant: variability in learners' digital skills, dependence on stable digital infrastructure, need for educator training in digital pedagogy. To overcome this challenge, digital tools are usually accompanied by: clear guidance and scaffolding, support for digital skill development, alternative formats when necessary.

Despite the potential of e-learning, challenges remain in ensuring the 'circularity of learning environments' themselves, reducing the digital footprint of education and ensuring that online tools are as sustainable as the topics they teach (Morales et al., 2022). Future research should focus on the long-term impact of MOOCS on behavioural change and the integration of advanced technologies like AI in personalizing CE education.

Building a Knowledge Repository: The Digital Library of Relevant Materials

Purpose and Concept of the Digital Library

A digital library is a system that provides organised access to digital objects (texts, images, audio, video, datasets) through networked environments, enabling discovery, retrieval, preservation, and reuse. Its core purpose is to support learning, research, and scholarship by making cultural, scientific, and educational resources Findable, Accessible, Interoperable, and Reusable (FAIR) within and across institutions. This

concept encompasses metadata creation and management, information organisation, user-centred design, and interoperable technologies that allow diverse users to locate and use digital materials efficiently. Multiple sources converge on these points, emphasising metadata as a primary enabler of findability and interoperability, and the digital library as both a repository and an access/learning platform that evolves with user needs and technological change (Fox & Urs, 2002; Cool & Ng, 2013; Zeng, 2019; Nikolaidou et al., 2005).

In addition to conceptual definitions, research on digital library systems also emphasises the importance of evaluation frameworks and software infrastructures that ensure functionality, usability, and scalability. For example, checklists and evaluation models for digital library software highlight criteria such as accessibility, metadata quality, interoperability, and user experience as essential components of effective digital repositories (Goh et al., 2006; Foo & Theng, 2004). These perspectives further reinforce the understanding of digital libraries as complex socio-technical systems rather than merely collections of digital content.

Digital libraries serve multiple interrelated purposes that support access, preservation, and use of digital knowledge. First, they enhance discoverability and access by enabling diverse user groups (such as scholars, students, and the general public) to efficiently locate digital resources through structured metadata, advanced search interfaces, and interoperable systems (Cool & Ng, 2013; Zeng, 2019; Nikolaidou et al., 2005). Second, they play a crucial role in preservation and stewardship, ensuring long-term access to cultural heritage, scientific data, and scholarly outputs. This is achieved through the use of standardised metadata frameworks and archival practices that support sustainability and interoperability (Cool & Ng, 2013; Ferro & Silvello, 2013; Neugebauer et al., 2012). Third, digital libraries promote interoperability and reuse by enabling integration across heterogeneous systems such as libraries, archives, and museums. Through shared metadata standards and linked data approaches, they facilitate cross-platform discovery, data reuse, and new research opportunities (Fox & Urs, 2002; Zeng, 2019; Chi et al., 2006; Nikolaidou et al., 2005). Furthermore, there is a growing emphasis on user-centred design and contextual relevance, where metadata, interfaces, and content organisation are adapted to user needs. This includes incorporating user-generated input, such as tagging and feedback, to enhance findability and usability (Matu-

siak, 2006; Therrell, 2019; Hu et al., 2018; Cairns, 2013; Klavans et al., 2013). Finally, digital libraries increasingly support digital humanities and data science, providing infrastructures for semantic enrichment, linked data, and advanced analytical workflows. These capabilities enable new forms of knowledge creation and interdisciplinary research (Hyvönen, 2023; Zeng, 2019; Chi et al., 2006; Saumure & Shiri, 2008).

In the case of the EDU4PlastiCircular project, the Digital Library serves as a strategic and pedagogical response to the growing need for structured, accessible, and high-quality knowledge on environmental sustainability, particularly plastics and the circular economy. As highlighted in the analysed study, awareness-raising and capacity-building are essential for enabling systemic transitions toward sustainable and circular models (Dermol & Dermol, 2024). In this context, the Digital Library is conceptualised not merely as a repository of materials but as a comprehensive digital learning ecosystem. It supports the dissemination of interdisciplinary knowledge, combining environmental science, technological innovation, and behavioural change. Its purpose aligns closely with the broader objectives of contemporary sustainability education: promoting informed decision-making, fostering environmental responsibility, and developing the competencies needed to address complex ecological challenges. The Digital Library hosted on microplastics.today exemplifies this approach and serves as a central platform for accessing project outputs, educational materials, and sustainability-related knowledge resources. It is embedded within the Erasmus+ project framework and contributes to the development of green skills, awareness, and sustainable practices related to plastics and the circular economy. By integrating educational materials with digital accessibility, it supports both formal and informal learning environments.

Comparing the Digital Library hosted on microplastics.today with the theoretical definition of a digital library, the analysis shows that the Digital Library largely fulfils key functions of a digital library, particularly in terms of accessibility, content organisation, and support for education. It is important to emphasise that this Digital Library was developed within an Erasmus+ project, with the primary aim of disseminating educational materials and sharing the knowledge generated in the field of plastics and the circular economy. Its strengths are reflected in its well-structured thematic content, multilingual accessibility, and clear focus on learning and awareness-raising. However,

from a technical and infrastructural perspective, it only partially aligns with the characteristics of advanced digital library systems. However, there is limited use of structured metadata, an absence of standardised schemas and interoperability protocols, and a lack of advanced functionalities such as enhanced search capabilities or user-generated metadata. Therefore, it can best be described as a structured, content-rich digital repository with strong dissemination and educational functions, rather than as a fully developed interoperable digital library infrastructure in the strict technical sense (Nikolaidou et al., 2005; Neugebauer et al., 2012; Zeng, 2019).

Development Process

The development of the Digital Library is grounded in both pedagogical principles and empirical insights derived from the analysis of online courses in circular economy education. These findings indicate that effective digital learning environments must be user-centred, modular, and adaptable to diverse audiences, including students, educators, professionals, and policymakers (Dermol & Dermol, 2024). In this context, the Digital Library hosted on the microplastics.today platform was not developed as an isolated output but as part of a structured and iterative project process embedded within the Erasmus+ project EDU4PlastiCircular.

The materials in the Digital Library represent a comprehensive, systematically developed collection of texts, videos, presentations, and other educational resources created during the elaboration of project deliverables. The development process followed a logical progression of activities, including:

- Identification of knowledge gaps and collection of best practices (D2.1);
- Development of curriculum and training methodology (D2.2);
- Creation of open-access digital content and e-learning modules;
- Integration with broader e-learning platforms and training programmes.

More specifically, the Digital Library builds on key outputs, including the analysis and synthesis of existing training programmes, the definition of training personas, the development of learning objectives, curricula, and course structures, and the design of learning paths and

assessment tools (e.g., quizzes and exam questions). Additional components include guidelines for implementing training at higher education institutions, definitions of pedagogical approaches for both online and face-to-face learning, and the conduct of train-the-trainers activities, including presentations and webinars. These outputs were progressively transformed into digital learning materials and curated within the Digital Library, ensuring coherence, pedagogical consistency, and practical applicability. Similar challenges in curriculum design and implementation have been identified in sustainability-focused education initiatives, where the adoption of new content often depends on institutional support, teacher readiness, and alignment with existing curricula (Goodale, 2020).

Content selection within the Digital Library follows clearly defined criteria:

- Scientific reliability and alignment with current research;
- Relevance to circular economy and plastic waste management;
- Applicability to real-world contexts;
- Accessibility and usability for diverse user groups.

Importantly, the development process reflects the need identified in the literature for combining theoretical knowledge with applied learning approaches, such as case studies, practical tools, and real-world examples (Whiter, 2022). This ensures that the Digital Library is not only informative but also actionable, enabling users to translate knowledge into practice.

In this sense, the Digital Library functions as a centralised platform for integrating, disseminating, and reusing knowledge, where project-generated content is systematically organised and made accessible. It also embodies the project's broader objective of developing open training materials, e-learning content, and digital resources to build green skills and promote sustainable practices.

The benefits of this development approach extend across multiple stakeholder groups. For higher education institutions, the Digital Library provides structured curricula, teaching materials, and methodological guidelines that support curriculum innovation and the integration of sustainability topics into formal education. For teachers and trainers, it offers pedagogically grounded resources and training tools to enhance teaching effectiveness and facilitate the delivery of engag-

ing, up-to-date content. For students and learners, it enables flexible, self-directed learning through access to diverse and multimedia-rich materials, supporting the development of knowledge and competencies in the circular economy and environmental sustainability.

Furthermore, professionals and industry stakeholders benefit from practical insights, case-based knowledge, and tools that can be applied in organisational contexts, supporting the implementation of sustainable practices. Policymakers and public sector stakeholders can use the Digital Library as a source of consolidated knowledge and best practices to inform decision-making. Finally, for the broader public, the Digital Library raises awareness and promotes environmentally responsible behaviour by making complex sustainability topics accessible and understandable.

Overall, the Digital Library enhances the transferability, scalability, and long-term impact of project results by ensuring that the knowledge generated within the Erasmus+ project is not only preserved but also actively disseminated, reused, and further developed across different educational and professional contexts.

Structure and Content of the Digital Library

A key strength of the Digital Library lies in its structured, multi-layered content organisation, which reflects both pedagogical logic and the thematic coverage of circular economy education.

The Digital Library is available on microplastics.today platform includes a wide range of content types, such as:

- Presentations;
- Readings and theoretical materials;
- Terminology resources;
- Worksheet templates;
- Videos and multimedia content;
- Project deliverables and reports;
- Newsletters and awareness materials.

These materials are systematically categorised into thematic areas, including:

- Plastics in everyday life and environmental impact;
- Plastic materials and manufacturing technologies;

- Circular economy principles and applications;
- Plastic waste management and recycling;
- Innovation in plastics and sustainable materials.

For example, introductory modules such as 'Plastics in Our Daily Lives' provide foundational knowledge on the use, impact, and sustainability implications of plastics, while more advanced materials address manufacturing technologies and circular economy integration.

An important feature of the Digital Library is its multilingual accessibility, with materials available in several languages (e.g., Slovenian, Spanish, Romanian, Italian), which significantly enhances inclusivity and dissemination potential.

The thematic structure of the Digital Library strongly aligns with the key content areas identified in the analysed online courses, including circular design, waste management, business models, and policy frameworks (Dermol & Dermol, 2024). This alignment confirms that the Digital Library reflects current trends and priorities in sustainability education.

The materials developed within the EDU4PlastiCircular project can be understood as Open Educational Resources (OER), which strongly reinforces the conceptual and functional role of the Digital Library. OER are part of a broader movement of open education that encompasses Open Educational Practices (OEP), open pedagogy, open access, and open licensing frameworks. This broader ecosystem reflects a shift from simply providing access to content toward enabling collaborative, participatory, and flexible learning environments (Shareefa et al., 2023; Benlamri et al., 2016).

From a structural perspective, the Digital Library aligns with established OER taxonomies, as it includes a wide range of resource types, such as course modules, learning objects, video materials, training presentations, and supporting documents. These correspond to commonly recognised forms of OER, including open courseware, multimedia learning materials, and supplementary resources that support diverse learning pathways (Cirulli et al., 2016; Shareefa et al., 2023; Wiley, 2020; Benlamri et al., 2016). In addition, such resources are typically designed to be reusable and adaptable, often supported by open licensing frameworks such as Creative Commons, which operationalise the principles of openness through the well-known 5RS (retain, reuse, revise, remix, redistribute) (Pineda & Guerrieri, 2021; Shareefa et al., 2023). The

development and use of OER are also closely linked to broader discussions on openness in education, which emphasise not only access to resources but also the transformation of educational practices toward more collaborative and participatory models (Peters & Brítez, 2008). In this context, digital repositories play a crucial role in supporting open knowledge infrastructures and facilitating the sharing and adaptation of educational content across institutions.

The integration of OER within a Digital Library also reflects the development of open learning ecosystems, where repositories, metadata practices, and interoperable infrastructures support discoverability and reuse across platforms. Such ecosystems are increasingly connected with learning management systems (LMS), analytics tools, and broader educational networks, enabling scalable and sustainable knowledge dissemination (Otto & Kerres, 2022; Otto et al., 2021; Benlamri et al., 2016; Wiley, 2020). In this sense, the Digital Library functions as a key node within a wider ecosystem of digital learning and knowledge sharing. Furthermore, the integration of repositories with other digital systems, such as learning management systems and institutional platforms, is increasingly recognised as a key factor for enhancing usability and supporting seamless access to learning resources (Penello Temporao & Pavani, 2018).

The educational value of OER further strengthens the rationale for developing and maintaining Digital Libraries. One of the primary purposes of OER is to enhance access, affordability, and equity in education by reducing financial barriers and increasing the availability of high-quality learning materials (Geith & Vignare, 2008; Haughery et al., 2021; Otto & Kerres, 2022; Otto et al., 2021; Shareefa et al., 2023; Wiley, 2020). By making project outputs openly accessible, the Digital Library contributes to more inclusive educational opportunities and supports learners who may otherwise lack access to specialised knowledge.

Beyond access, OER also offer significant pedagogical potential, enabling open pedagogy and innovative teaching practices. They support collaborative learning, co-creation of knowledge, and flexible learning pathways, allowing both educators and learners to adapt materials to specific contexts and needs (Peters & Brítez, 2008; Shareefa et al., 2023). This flexibility is particularly relevant in sustainability education, where interdisciplinary approaches and contextual adaptation are essential.

At the same time, research highlights the importance of systematic

development, evaluation, and curation of OER. Institutions developing digital repositories must address challenges related to discoverability, licensing clarity, quality assurance, and long-term sustainability (Geith & Vignare, 2008; Otto & Kerres, 2022; Wiley, 2020). The effectiveness of OER-based systems also depends on their ability to support diverse learners through accessible design and inclusive practices, including alignment with principles such as Universal Design for Learning (UDL) (Moon & Park, 2021; Shareefa et al., 2023). Issues related to metadata quality, standardisation, and consistency remain central challenges in digital repositories, as poorly structured metadata can significantly reduce discoverability and usability of resources (Stvilia et al., 2006).

From a practical perspective, the implementation of OER within a Digital Library requires a clear strategic approach, including the definition of openness principles, the use of interoperable repository infrastructures, and continuous evaluation of impact and usability (Wiley, 2020; Shareefa et al., 2023; Otto & Kerres, 2022). While openness facilitates reuse and scalability, it must be balanced with considerations of quality, contextual relevance, and pedagogical effectiveness.

Finally, the relationship between OER and digital libraries is particularly significant. OER dissemination relies on digital library-like infrastructures, including metadata, repositories, and interoperability standards, which support access, reuse, and long-term preservation. This convergence highlights the role of Digital Libraries as essential components of modern learning ecosystems, bridging information management practices with educational innovation (Saumure & Shiri, 2008; Krahmer et al., 2021; Shareefa et al., 2023; Wiley, 2020).

In this context, the Digital Library developed within the Erasmus+ project can be seen not only as a repository of materials but as an open, scalable, and pedagogically grounded knowledge infrastructure, supporting both the dissemination of project results and the broader goals of open and inclusive education.

Digital Accessibility and User Experience

The Digital Library demonstrates a strong commitment to accessibility and user-centred design, positioning it as an inclusive digital environment that supports a wide range of users. Digital accessibility refers to the design and delivery of digital content in ways that enable people with diverse abilities-including those with visual, auditory, motor, cognitive, or situational limitations-to perceive, understand, navigate, and

interact effectively with digital systems (Putra et al., 2024; Halbach & Haugstvedt, 2021; Gould et al., 2021). In this sense, accessibility is not a separate feature but an integral component of overall user experience (UX), ensuring that digital platforms are usable, equitable, and effective for all users (Bertot et al., 2006; Snead et al., 2005).

The Digital Library integrates several key features that enhance usability and inclusiveness. These include intuitive navigation and thematic categorisation, which support efficient information retrieval; responsive design, enabling access across different devices and contexts; and accessibility tools, such as text size adjustment and contrast settings, which improve readability and accommodate users with visual impairments. In addition, the platform provides open access to educational materials, reducing barriers to entry and supporting equitable participation in learning. Together, these features contribute to a positive, inclusive user experience, aligning with established accessibility and usability principles in digital environments.

These design choices are particularly important in addressing well-documented barriers in online education, such as the digital divide and varying levels of digital literacy (Jeruszka, 2023). By incorporating accessibility features and offering multilingual content, the Digital Library expands its reach and ensures that a broader and more diverse audience can engage with sustainability-related knowledge. This reflects a user-centred design approach, where content organisation, interface design, and functionality are aligned with the needs and capabilities of different user groups (Putra et al., 2024; Halbach & Haugstvedt, 2021).

From a technical and standards perspective, digital accessibility is commonly guided by frameworks such as the Web Content Accessibility Guidelines (WCAG), which define principles of perceivability, operability, understandability, and robustness. While not all technical compliance details are explicitly visible, the Digital Library reflects several of these principles through its emphasis on readable formats, structured content, and accessible interface design. Moreover, accessibility extends beyond web pages to include diverse content formats such as documents, videos, and interactive materials, all of which should be designed to support assistive technologies and enhance comprehension (Putra et al., 2024; Gould et al., 2021).

Importantly, accessibility is closely linked to user experience and evaluation practices. Integrating accessibility into UX design-through user-centred approaches and iterative testing-ensures that potential

barriers are identified and addressed early in the development process. In digital library contexts, this often involves combining usability testing with accessibility evaluation, including the participation of users with diverse needs (Putra et al., 2024; Bertot et al., 2006; Snead et al., 2005). Although such processes may not always be fully formalised in project-based platforms, the presence of user-friendly features suggests an awareness of these principles. Previous studies also highlight the importance of integrating accessibility evaluation with usability testing to ensure that digital platforms effectively meet the needs of diverse user groups, including those with disabilities (Snead et al., 2005; Bertot et al., 2006).

From a practical perspective, ensuring accessibility requires proactive planning and continuous improvement. Best practices include adopting inclusive design principles, providing alternative text for images, ensuring sufficient colour contrast, enabling keyboard navigation, and offering captions or transcripts for multimedia content (Putra et al., 2024; Halbach & Haugstvedt, 2021; Gould et al., 2021). In addition, the use of accessibility metadata in digital repositories can further enhance discoverability and support users who rely on assistive technologies.

At the same time, the literature highlights ongoing challenges and debates. These include potential trade-offs between visual design and accessibility, the need to ensure that open educational resources are also accessible, and the recognition that accessibility is not a one-time achievement but a continuous process of monitoring, testing, and adaptation (Putra et al., 2024; Snead et al., 2005; Alić, 2025). This perspective is particularly relevant for digital libraries, where content and technologies evolve over time.

In conclusion, the Digital Library reflects key principles of digital accessibility and user-centred design, contributing to an inclusive and effective learning environment. By combining accessible design features with structured content and open access, it supports a positive user experience and aligns with broader goals of equity and inclusion in digital education. At the same time, continued development and evaluation are necessary to ensure that accessibility remains an ongoing priority and that the platform adapts to the evolving needs of its users.

Contribution to Environmental Education

The Digital Library represents an important contribution to environmental education by supporting both knowledge dissemination and

capacity building, thereby enabling the development of competencies necessary for a transition toward a circular and climate-neutral economy. Environmental education (EE) is widely understood as a multidisciplinary and transformative process that equips learners with knowledge, skills, values, and attitudes required to understand and address environmental challenges (Parry & Metzger, 2023; Rahmawati et al., 2022; Abidin et al., 2024). Within this broader framework, the Digital Library functions as a practical tool that operationalises these principles through accessible and structured learning resources.

Environmental education extends beyond raising awareness and aims to foster critical thinking, problem-solving abilities, and action-oriented competences that support sustainable behaviour and decision-making. As emphasised in the literature, effective EE must move beyond theoretical understanding and enable learners to apply knowledge in real-world contexts (Dragomir et al., 2019). The Digital Library responds to this need by integrating multiple forms of learning content, including theoretical materials, practical tools, and case-based learning resources, thereby supporting both conceptual understanding and practical application.

This combination reflects contemporary approaches to EE, which emphasise experiential, place-based, and applied learning. By incorporating real-world examples, project deliverables, and context-specific materials, the Digital Library enables learners to connect abstract concepts with concrete practices. Such an approach aligns with broader educational trends that promote interdisciplinary and action-oriented learning, often situated within the framework of Education for Sustainable Development (ESD) (Parry & Metzger, 2023; Stewart et al., 2021; Bounnite, 2025). Through this integration, learners are encouraged not only to understand environmental issues but also to actively engage in addressing them.

Furthermore, the Digital Library supports key objectives of environmental education, including the development of environmental knowledge, pro-environmental attitudes, and sustainability-related skills. These include critical and systems thinking, collaboration, and the ability to design and implement solutions to environmental challenges (Rahmawati et al., 2022; Bounnite, 2025). By offering diverse, multimedia-rich resources, the platform accommodates different learning styles and supports inclusive, flexible learning pathways.

From a pedagogical perspective, the Digital Library also facilitates

the integration of environmental education into various educational contexts. It can support formal education through curriculum integration, as well as non-formal and informal learning, enabling lifelong learning and broader public engagement. This is particularly important given that effective environmental education often requires cross-curricular approaches, teacher training, and institutional support to ensure meaningful implementation (Abidin et al., 2024; Stewart et al., 2021).

At the same time, the Digital Library addresses some of the practical challenges in environmental education, such as limited access to high-quality materials, a lack of teaching resources, and the need for adaptable, context-relevant content. By providing openly accessible, structured, and reusable materials, it helps reduce these barriers and supports educators and learners in implementing sustainability-oriented learning practices.

In conclusion, the Digital Library can be understood as a key enabler of contemporary environmental education, bridging the gap between knowledge and action. By combining theoretical foundations with applied learning resources and aligning with the principles of EE and ESD, it supports the development of environmentally responsible individuals and contributes to broader societal transitions toward sustainability.

Challenges and Lessons Learned

Despite its conceptual strengths and pedagogical value, the development and implementation of the Digital Library reveal a number of structural, technological, and educational challenges that are characteristic of digital learning environments and repository-based systems.

One of the primary challenges is maintaining up-to-date and relevant content. As sustainability, circular economy practices, and technological solutions evolve rapidly, digital repositories risk becoming outdated if continuous content revision and curation are not ensured. This challenge is particularly pronounced in project-based digital libraries, where content is often developed within a fixed timeframe and requires post-project sustainability mechanisms to remain current and impactful.

Closely related is the issue of ensuring consistent quality across diverse materials. The Digital Library integrates a wide range of resources – including reports, videos, presentations, and training materials – de-

veloped by multiple partners. While this diversity enriches the repository, it also introduces variability in format, depth, pedagogical design, and scientific rigour. Maintaining coherence and quality standards across such heterogeneous content requires clear editorial guidelines, quality assurance procedures, and ongoing review processes.

Another critical challenge concerns user engagement and learning effectiveness. As highlighted in the analysis of online courses in circular economy education, there is a strong tendency toward traditional, lecture-based teaching formats, even within digital environments (Dermol & Dermol, 2024). This tendency is also reflected in digital repositories, which may primarily function as content storage systems rather than interactive learning environments. Without integrating participatory elements, digital libraries risk promoting passive consumption of information rather than active knowledge construction and skill development.

In addition, technological and cognitive barriers continue to affect the accessibility and usability of digital learning resources. These include differences in digital literacy, varying levels of familiarity with online learning platforms, and limitations related to access to devices or stable internet connections. Even when accessibility features are implemented, users may still face challenges in navigating large volumes of content or efficiently identifying relevant materials. This highlights the importance of intuitive design, structured categorisation, and user guidance within digital libraries.

The development process also reveals limitations in relation to technical infrastructure and interoperability. As noted in earlier sections, the Digital Library functions effectively as a structured repository but lacks some of the advanced features of fully developed digital library systems, such as sophisticated metadata schemas, interoperability protocols, and enhanced search functionalities. This limits its integration with broader knowledge ecosystems and reduces opportunities for automated data exchange, reuse, and scalability.

These challenges provide several important lessons for the future development of digital libraries in educational and sustainability contexts. First, there is a clear need to move beyond static repositories toward dynamic, continuously updated knowledge platforms, supported by long-term maintenance strategies and institutional commitment. Second, quality assurance and standardisation mechanisms should be embedded throughout the content development process to ensure

consistency and reliability across materials. Third, and perhaps most importantly, digital libraries should increasingly incorporate interactive and participatory learning features, such as quizzes, discussion forums, collaborative tools, and problem-based learning scenarios. Such elements can transform digital libraries from passive information repositories into active learning environments that support deeper engagement and knowledge application.

Finally, addressing technological and cognitive barriers requires a continued emphasis on user-centred design, accessibility, and guidance, ensuring that diverse user groups can effectively navigate and benefit from the available resources. This includes not only technical accessibility but also pedagogical clarity and support for different learning pathways.

In conclusion, while the Digital Library represents a valuable and impactful educational resource, its development highlights the importance of continuous improvement, integration of interactive elements, and alignment with evolving digital learning practices. These lessons are essential for enhancing the long-term effectiveness, usability, and sustainability of digital knowledge repositories in environmental education and beyond.

Future Development and Sustainability

The future development of the Digital Library should move beyond its current role as a structured repository toward a more interactive, adaptive, and sustainable digital learning ecosystem. While the existing platform successfully supports knowledge dissemination and access to educational materials, further enhancements are necessary to maximise its pedagogical impact, user engagement, and long-term relevance.

One of the key directions for future development is integrating interactive learning tools and virtual environments. The current structure, which is largely based on static resources such as documents and videos, could be complemented by simulations, virtual labs, and scenario-based learning tools. Such features would enable users to experiment with real-world sustainability challenges, such as plastic lifecycle analysis or circular economy decision-making processes. This shift from passive content consumption to active engagement is essential for supporting deeper learning and skill development.

Closely related is the incorporation of gamification elements, which

can significantly enhance motivation and user participation. Features such as progress tracking, badges, interactive challenges, and achievement systems can encourage continuous learning and increase user retention. Gamification has been widely recognised as an effective strategy for improving engagement in digital education environments, particularly when addressing complex and interdisciplinary topics such as environmental sustainability.

Another important direction is the development of personalised learning pathways. Given the diversity of target users-including students, educators, professionals, and policymakers-the Digital Library should support adaptive learning experiences tailored to different needs, prior knowledge levels, and learning goals. This could involve guided learning journeys, modular course structures, and recommendation systems that suggest relevant materials based on user profiles and behaviour. Such personalisation would enhance both usability and learning effectiveness, making the platform more responsive to individual learning contexts.

Furthermore, there is significant potential for stronger integration with online courses, learning management systems (LMS), and MOOCS. While the Digital Library already contains a wealth of structured educational materials, linking these resources with formalised courses, certification pathways, and assessment tools would increase their practical value. This integration would also support blended learning models and facilitate the incorporation of Digital Library content into formal education programmes and professional training.

In terms of content development, the analysis highlights the need to expand and continually update thematic coverage, particularly in emerging areas of sustainability and circular-economy education. As suggested by the analysed study (Dermol & Dermol, 2024), future content should include advanced and forward-looking topics such as innovative and bio-based materials, digital monitoring and tracking tools (e.g., IOT and data-driven systems), and policy frameworks for implementing the circular economy. Including such topics would ensure that the Digital Library remains aligned with current research, industry developments, and policy priorities.

Equally important is the establishment of sustainable governance and maintenance mechanisms. Long-term sustainability of the Digital Library requires clear ownership, regular content updates, and dedicated resources for technical maintenance and development. Without

such structures, the platform risks gradually losing relevance and usability after the project's completion. Sustainable models may include institutional embedding, partnerships with educational organisations, or integration into broader European or international knowledge platforms.

In addition, future development should strengthen the Digital Library's technical infrastructure, particularly in metadata standardisation, interoperability, and advanced search functionality. Enhancing these aspects would improve discoverability, enable integration with other repositories, and support the reuse of materials across different platforms and contexts.

Finally, continuous attention should be given to user engagement, accessibility, and evaluation. This includes incorporating user feedback mechanisms, conducting usability and accessibility testing, and monitoring usage patterns and learning outcomes. Such evaluation processes are essential for ensuring that the Digital Library evolves in line with user needs and technological developments.

In conclusion, the long-term sustainability and impact of the Digital Library depend on its ability to evolve from a static repository into a dynamic, user-centred, and interoperable learning environment. By integrating interactive features, expanding content, enhancing technical capabilities, and ensuring sustainable governance, the Digital Library can become a robust and scalable platform that supports environmental education and contributes to broader sustainability transitions.

Digital Tools for Sustainable Engagement

The Digital Frontier in Environmental Education

Digital technologies are fundamentally transforming how environmental education (EE) is designed, delivered, and experienced. They enable more flexible, scalable, and interactive learning environments, supporting new forms of knowledge construction, collaboration, and dissemination. At the same time, the effectiveness of these technologies depends on their capacity to foster meaningful engagement, interaction, and accessibility, rather than merely digitising traditional teaching practices (Guzmán et al., 2022). Within this evolving landscape, digital platforms-such as the Digital Library and associated online environments-represent key components of a broader 'digital frontier' in environmental education, opening new possibilities for learning, communication, and participation.

From a functional perspective, digital technologies in EE encompass a wide range of tools and platforms. These include digital content repositories, such as e-books, multimedia resources, and online learning materials, which serve as structured sources of environmental knowledge and support multimodal learning. In this context, the Digital Library can be understood as part of a wider ecosystem of digital knowledge infrastructures that facilitate access to curated educational resources and support cross-disciplinary learning. The effectiveness of such repositories depends not only on the availability of content but also on the organisation, accessibility, and integration of knowledge resources within broader digital ecosystems (Li et al., 2022; Mejabi et al., 2016).

In addition, interactive visualisation and geospatial technologies, including GIS tools, GPS applications, and platforms such as StoryMaps, are increasingly important in environmental education. These tools enable learners to explore environmental issues through data analysis, spatial representation, and place-based investigation, thereby strengthening connections between local contexts and global sustainability challenges (Cisneros et al., 2023). Such approaches contribute to the development of eco-digital storytelling practices in which learners actively engage in interpreting and communicating environmental data.

A further important dimension is the use of digital storytelling and media-rich learning environments, which combine text, images, audio, and video to communicate environmental concepts. These approaches enhance learners' ability to articulate complex issues, develop critical thinking, and engage in science communication, while also fostering global citizenship and sustainability literacy. By enabling learners to connect personal experiences with broader environmental narratives, digital storytelling supports both cognitive and affective dimensions of learning.

Digital technologies also play a crucial role in supporting collaborative and participatory pedagogies. Information and communication technologies (ICT), including learning management systems (LMS), online collaboration tools, blogs, and social media platforms, facilitate interaction among learners, educators, and communities. These tools support inquiry-based learning, reflection, and co-creation of knowledge, and they enable the implementation of blended and remote learning models (Sadieda & Sutini, 2023). In this regard, platforms such

as Digital Libraries not only provide access to content but also function as hubs for knowledge exchange and collaborative learning.

Another significant contribution of digital technologies lies in assessment and learning analytics. Digital platforms enable the implementation of online assessments, performance-based tasks, and real-time feedback mechanisms, and support data-driven evaluation of learning outcomes. These tools can be used to monitor the development of environmental literacy, digital competencies, and sustainability-related skills, and to inform the continuous improvement of educational programmes (Rohmanurmeta & Dewi, 2020).

From a pedagogical perspective, the integration of digital technologies in environmental education must be carefully aligned with established principles of experiential, place-based, and interdisciplinary learning. Rather than replacing hands-on experiences, digital tools should complement and enhance them by enabling data collection, documentation, and sharing of environmental observations (Borisenoka, 2024; Rahmawati et al., 2022; Sadieda & Sutini, 2023). This is particularly important in sustainability education, where real-world engagement and contextual understanding are essential.

Moreover, digital technologies support the integration of environmental education with STEAM (science, technology, engineering, arts, and mathematics) approaches, enabling learners to address complex sustainability challenges from multiple perspectives. By combining technological tools with ethical, social, and environmental considerations, such approaches foster holistic and systems-oriented thinking (Rahmawati et al., 2022; Bounnite, 2025; Cisneros et al., 2023).

However, the successful implementation of digital technologies in environmental education also depends on several enabling conditions. These include digital literacy among learners and educators, access to appropriate infrastructure, and the availability of pedagogically meaningful resources (Sadieda & Sutini, 2023). Without these conditions, digital tools risk reinforcing existing inequalities, particularly in contexts where access to technology and digital skills is uneven.

In practical terms, digital technologies are already being applied in a variety of educational contexts. These include the use of digital content libraries and repositories to support structured learning pathways, the implementation of GIS-based projects and environmental storytelling, and the integration of citizen science initiatives that encourage public participation and environmental engagement (Cisneros et al., 2023). In

addition, digital platforms play a key role in teacher professional development, providing opportunities for continuous learning, collaboration, and exchange of best practices (Sadieda & Sutini, 2023).

Despite these opportunities, several challenges remain. These include issues related to the digital divide, the need for pedagogical alignment and curriculum integration, and the importance of teacher readiness and professional development. Furthermore, the empirical evidence on the impact of digital technologies in environmental education remains context-dependent, highlighting the need for more rigorous and longitudinal research.

In conclusion, digital technologies represent powerful enablers of innovation in environmental education, offering new opportunities for engagement, collaboration, and knowledge creation. However, their effectiveness depends on thoughtful integration with pedagogical principles, attention to accessibility and equity, and continuous evaluation of their impact. Within this context, Digital Libraries and similar platforms play a crucial role as bridging infrastructures, connecting knowledge resources, learning environments, and communities in support of sustainable development.

Project Website as a Learning Hub

The microplastics.today platform functions as a central digital learning hub that integrates the Digital Library, project outputs and deliverables, and training materials and e-learning resources into a unified environment. Rather than serving merely as a repository of information, the platform operates as a connecting infrastructure that links knowledge creation, organisation, and dissemination with user engagement and learning processes. In this sense, it reflects the broader role of digital platforms within the evolving 'digital frontier' of environmental education, where technology supports not only access to content but also interaction, participation, and knowledge exchange (Guzmán et al., 2022).

Building on the principles outlined above, the platform embodies key characteristics of effective digital learning environments. It provides structured, thematic access to interdisciplinary knowledge on plastics, sustainability, and the circular economy, while supporting open access and flexible learning pathways. The integration of diverse content types (ranging from reports and presentations to multimedia materials) enables users to engage with knowledge in multiple

ways, thereby supporting different learning preferences and contexts.

Importantly, the platform is designed to address a wide range of users, including educators, students, professionals, and the general public. This aligns with findings from the analysed study, which emphasise that digital learning environments in circular economy education should be user-centred, modular, and adaptable to diverse audiences (Dermol & Dermol, 2024). As such, the website functions as a dynamic learning ecosystem that facilitates knowledge transfer across institutional and societal boundaries, contributing to the broader goals of environmental education and sustainable development.

Social Media and Communication Channels

Social media platforms and communication channels, such as Facebook and project newsletters, extend the reach and impact of digital learning environments by enabling continuous interaction and engagement with diverse audiences. In contrast to static digital repositories, these tools provide dynamic and responsive communication spaces in which information can be shared, discussed, and co-created. This ongoing interaction is essential for maintaining engagement in online learning contexts, as highlighted by Mucundanyi (2021), who emphasises the importance of sustained communication in supporting learner participation and motivation. Sustained engagement in digital learning environments also depends on the design of interactive communication strategies and continuous learner support, which are essential for maintaining motivation and participation (Robertson, 2021).

From a pedagogical perspective, social media can be understood as part of a broader ecosystem of informal and networked learning environments. These platforms facilitate peer-to-peer interaction, collaborative knowledge construction, and the dissemination of ideas beyond formal educational settings. In the context of environmental education, they also support awareness-raising and public engagement by enabling the communication of sustainability-related topics in accessible and engaging formats.

Furthermore, social media contributes to the development of eco-digital storytelling practices, where environmental issues are communicated through visual, narrative, and multimedia content. This not only enhances understanding but also fosters emotional engagement and a sense of connection to environmental challenges. In this way,

social media and communication channels complement the Digital Library by transforming it into an interactive and socially embedded learning ecosystem.

Local Campaigns for Community Engagement

Local campaigns play a crucial role in bridging the gap between digital knowledge and real-world action. While digital platforms provide access to information and learning resources, local initiatives enable individuals and communities to apply this knowledge in practice. This connection is particularly important in environmental education, where the ultimate goal is not only to increase awareness but also to promote behavioural change and active participation in sustainability initiatives.

Such campaigns align with the principles of experiential and place-based learning, which emphasise the importance of engaging learners in real-life contexts and local environments (Rahmawati et al., 2022; Borisenoka, 2024). By addressing locally relevant environmental issues, they enhance the contextual relevance of knowledge and encourage community involvement. This, in turn, strengthens the impact of educational interventions and supports the development of environmentally responsible behaviours.

The integration of digital and local approaches represents a hybrid model of learning in which online resources provide the theoretical foundation, while offline activities enable practical application. This synergy ensures that knowledge is not only disseminated but also internalised and translated into action. As a result, local campaigns function as an essential component of a comprehensive environmental education strategy, linking digital learning ecosystems with societal transformation.

Digital Tools Enhancing Learning and Participation

The Digital Library incorporates a wide range of digital tools that support learning and participation, including textual materials, multimedia content, and various supporting resources such as worksheets and templates. This diversity of formats enables multimodal learning, which is particularly important in digital environments where users engage with content in different ways and contexts. By combining visual, textual, and interactive elements, the platform enhances comprehension, retention, and engagement.

However, despite these advantages, the analysis of online courses in circular economy education reveals a continued reliance on traditional, content-centred approaches, with limited integration of interactive and collaborative learning methods (Dermol & Dermol, 2024). This reflects a broader challenge in digital education, where technological tools are often used to replicate conventional teaching practices rather than to transform them (Guzmán et al., 2022).

To address this limitation, there is a need to further develop participatory and learner-centred approaches, including collaborative learning environments, problem-based learning, and interactive simulations. Such approaches would enable learners to actively engage with content, apply knowledge in practical contexts, and develop higher-order skills such as critical thinking and problem-solving. In this sense, the future development of digital tools should focus on enhancing interactivity and participation, thereby transforming the Digital Library into a more dynamic and engaging learning environment.

Impact on Learning and Behaviour Change

Digital tools play a significant role in enhancing learning outcomes and supporting behavioural change in environmental education. By increasing accessibility to knowledge, they enable learners from diverse backgrounds to engage with sustainability-related topics, regardless of geographical or institutional constraints. At the same time, the use of multimedia and interactive elements contributes to higher levels of engagement and supports more effective knowledge acquisition.

Beyond cognitive learning, digital tools also contribute to the development of practical skills and competencies that are essential for addressing environmental challenges. By integrating theoretical knowledge with real-world examples and applied learning materials, digital platforms support a deeper understanding of complex issues such as plastic waste management and circular economy practices. This aligns with the broader objectives of environmental education, which emphasise not only knowledge acquisition but also the development of attitudes and behaviours that support sustainability (Dragomir et al., 2019).

Importantly, the combination of structured content and interactive learning opportunities creates conditions that can foster behavioural change. When learners are actively engaged and able to relate knowledge to their own experiences and contexts, they are more likely to

adopt sustainable practices. In this way, digital tools serve as important enablers of both individual and collective transformation toward more sustainable ways of living.

Challenges and Opportunities

While digital tools offer immense potential for environmental education, their integration introduces several critical challenges that warrant careful consideration and strategic management. Chief among these concerns is the digital divide—a disparity characterized by unequal access to technology, reliable infrastructure, and digital literacy skills. This gap risks excluding marginalized learners and further widening existing socioeconomic inequalities, particularly within under-resourced communities. Furthermore, the sheer volume of available digital content frequently results in information overload, complicating the user's ability to filter relevant data, critically evaluate sources, and navigate learning materials effectively.

Another important challenge concerns the level of interactivity and the pedagogical effectiveness of digital tools. As noted earlier, many digital learning environments remain largely content-driven, with limited opportunities for active engagement and collaboration. This highlights the need for stronger alignment between technological solutions and pedagogical principles to ensure that digital tools effectively support learning objectives (Sadieda & Sutini, 2023).

At the same time, these challenges open up significant opportunities for innovation. Advances in digital technologies, such as gamification, adaptive learning systems, and simulation-based environments, offer new possibilities for enhancing engagement and learning outcomes. These approaches can support personalised learning experiences, increase motivation, and enable learners to explore complex environmental systems interactively (Sashank et al., 2023).

Looking ahead, the key opportunity lies in transforming digital platforms from static repositories into dynamic, user-centred learning ecosystems. This requires continuous development, integration of interactive features, and ongoing evaluation of user needs and learning outcomes. By addressing existing challenges and leveraging emerging technologies, digital tools can play a central role in advancing environmental education and supporting the transition toward sustainability. In addition, improving metadata practices and repository design remains a critical area for future development, as these elements directly

influence the usability, discoverability, and long-term sustainability of digital knowledge systems (Krahmer et al., 2021).

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Chapter Five

European Collaboration and Future Sustainability: Interconnections with Other Circular Economy Initiatives

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https://doi.org/10.53615/978-83-65020-56-7/185-198

The Power of Partnership: Cross-Border Cooperation in EDU4PlastiCircular project

The EDU4PlastiCircular project is built upon a robust transnational partnership comprising six key institutions across four European nations: Romania, Slovenia, Spain, and Italy. Figure 5.1 highlights the main

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

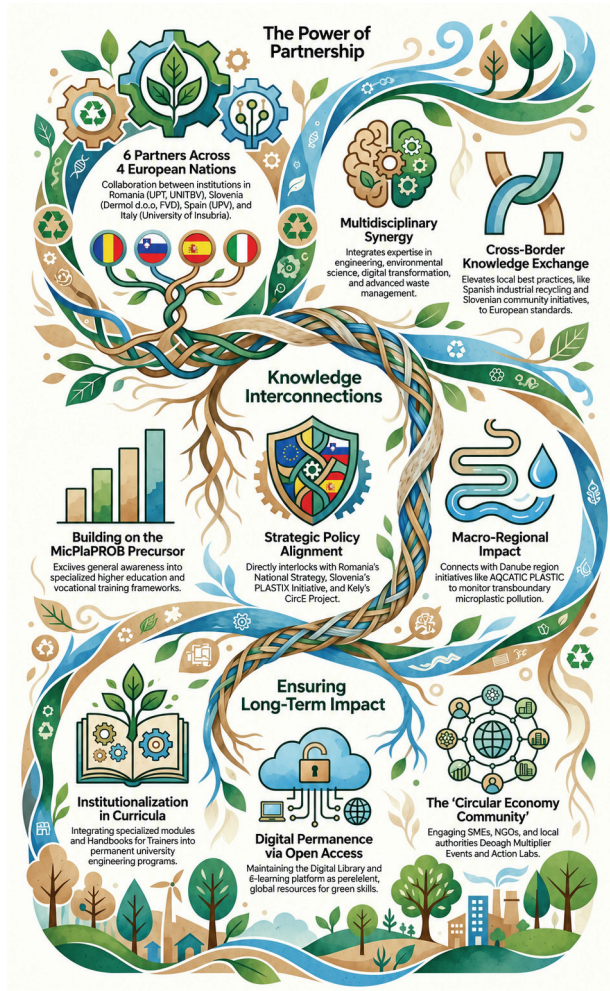


FIGURE 5.1
Overview of the Key Strategic Strengths of EDU4Plasti-Circular Project

NOTES Created by the Generative AI Software NotebookLM.

strengths of the partnership and key sustainability factors on the long term. This geographical and expertise-based diversity is fundamental to the project's ability to address the complex lifecycle of plastics and microplastics through a multidisciplinary lens. This geographical and expertise-based diversity is not accidental. It is a strategic response to the complex, non-linear lifecycle of plastics and the global nature of microplastic contamination. Table 5.1 summarises the strategic contribution and associated roles of each EDU4PlastiCircular consortium members.

The partnership operates on the principle of complementary exper-

TABLE 5.1 Partner Roles and Strategic Contributions

Country	Partner institution	Strategic role and expertise
Romania	Politehnica University Timisoara (UPT)	Leads engineering and technical education initiatives, focusing on sustainable technology development and the integration of circular economy into technical curricula.
Romania	Transilvania University of Brasov (UNITBV)	Provides specialized knowledge in environmental science and engineering, particularly in the assessment of plastic pollution in the Danube region.
Slovenia	Dermol svetovanje d.o.o.	Specialize in digital transformation and professional training, managing the project's E-learning infrastructure and digital pedagogical tools.
Slovenia	Faculty of Environmental Protection (FVO)	Focuses on sustainability education and the development of awareness-raising activities for young people regarding microplastics.
Spain	Universitat Politècnica de València (UPV)	Contributes expertise in advanced recycling technologies and environmental engineering, bridging academic research with industrial plastic management.
Italy	Università degli Studi dell'Insubria	Leads research on waste management and environmental sustainability, focusing on the chemical and biological aspects of plastic degradation.

tise, where the technical engineering capabilities of the Politehnica University Timisoara (UPT) and the Universitat Politècnica de València (UPV) are integrated with the environmental science and protection frameworks provided by the Transilvania University of Brasov (UNITBV) and the Faculty of Environmental Protection (FVO) in Velenje. This interdisciplinary synergy is further enhanced by the digital transformation expertise of Dermol svetovanje d.o.o. and the advanced waste management research conducted by the Università degli Studi dell'Insubria in Italy (Školnik Škrabe et al., 2025).

Cross-border cooperation within this consortium is operationalized through a series of highly integrated joint activities that transcend traditional academic boundaries. A primary example of this is the development of the D2.1 Gap Analysis and Collection of Best Practices, a comprehensive research effort that mapped the plastic management landscape across the four partner nations. This analysis did not merely

identify gaps but also documented successful local circular economy models through a series of 'Good Practice' videos. These videos serve as a repository of practical knowledge, showcasing industrial recycling innovations in Spain, community-led sustainability initiatives in Slovenia, and engineering solutions for waste reduction in Romania. Such collaborative efforts ensure that local best practices are elevated to a European standard, fostering a shared understanding of the circular economy that is sensitive to national specificities yet aligned with broader EU objectives.

Furthermore, the partnership emphasizes vertical cooperation, connecting higher education directly with real-world environmental remediation. The project's collaboration with Blended Intensive Programmes (BIP) has facilitated joint student-teacher initiatives focusing on 'preventing waste ending up into the environment.' These programs, such as the one between UPT and the University of Insubria, combine academic mobility with high-level research on emerging pollutants, allowing students to engage directly with the scientific and social complexities of plastic degradation. This transnational synergy creates a 'European identity' in environmental stewardship, where the collective intelligence of the consortium-manifested through joint publications, transnational meetings in Brasov, Velenje, and Oradea, and the co-creation of digital learning resources, exceeds the sum of its individual institutional contributions.

EDU4 PlastiCircular Knowledge Interconnection with other Projects and Initiatives

Beyond its immediate project lineage, EDU4 PlastiCircular is deeply integrated with macro-regional and national strategies that drive the circular transition in the four partner countries. In Romania, the project aligns with the National Strategy for Circular Economy (2022–2032),[1] which sets ambitious targets for municipal waste recycling. By training the next generation of 'Green Engineers' at Politehnica University of Timisoara (Romania) and Transilvania University of Brasov (Romania), the project provides the human capital necessary to implement these national frameworks. In Slovenia, the interconnection between EDU4 PlastiCircular and other initiatives is particularly strong

[1] More details at https://circulareconomy.europa.eu/platform/en/strategies/national-strategy-circular-economy-romania

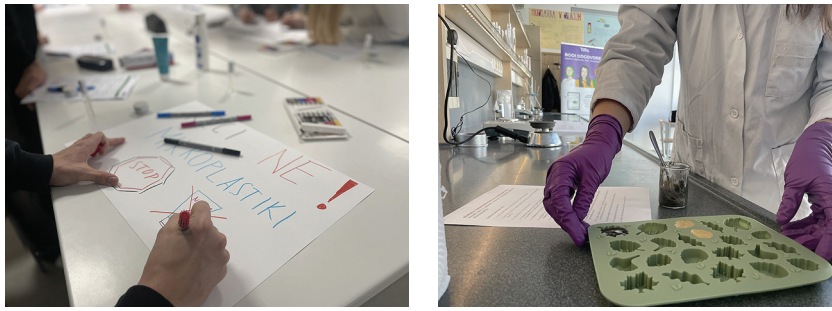


FIGURE 5.2 Hands-on Activities Within the Micro(μ)School program at the Faculty of Environmental Protection in Slovenia

due to the long term strategic focus of the Faculty of Environmental Protection (FVO) on microplastics, harmful substances, and circular economy education. Over the past years, FVO has coordinated or co created several Erasmus+ projects (e.g., MicPlaPROB, GreenGate, GreenGate2), national research activities, and regional awareness campaigns, which together form a coherent knowledge base that directly feeds into EDU4PlastiCircular. A distinctive feature of the Slovenian context is the systematic integration of digital learning environments, open educational resources (OER), and hands on laboratory and field activities (Školnik Škrabe, & Bubik, 2024). Through these approaches, FVO has developed a recognizable educational model that combines scientific accuracy with accessibility for diverse target groups, from secondary school students to university staff, youth workers, and adult learners. The Micro(μ)School programme, developed at FVO, represents one of the most visible outcomes of this interconnected ecosystem. It consolidates knowledge from multiple Erasmus+ projects and national initiatives into a flexible training model that includes workshops on microplastics in textiles, hidden plastics in cosmetics, and basic monitoring techniques for water and soil (Komeriki Kotnik et al., 2025). This model has been repeatedly tested, refined, and expanded, making it a key contribution of Slovenia to the EDU4PlastiCircular partnership.

In addition to educational projects, the project interlocks with the PLASTIX initiative and the SRIP – Circular Economy platform, while also linking with cutting-edge research projects like EMICOPLAST, which explores the use of engineered microbial consortia for plastic degradation. This interconnection ensures that the project's educa-

tional content is not only theoretically sound but also practically relevant to the Slovenian industrial and research landscape. The project's reach extends into the Mediterranean and Danube basins through its alignment with Interreg programs. In the Danube region, EDU4PlastiCircular connects with initiatives such as AQUATIC PLASTIC and MicroDrink, which focus on monitoring and mitigating microplastic pollution in riverine and drinking water systems. These interconnections allow the project to utilize real-world data and case studies on transboundary pollution, providing students with a holistic view of the environmental challenges facing European water bodies.

Similarly, in Spain, the project contributes to national waste management plans like the PEMAR 2025–2035 and regional policy integration efforts like the CircE Project. By weaving these diverse threads together, EDU4PlastiCircular acts as a central hub for circular economy knowledge, synthesizing outcomes from various Interreg, Horizon, and LIFE projects to deliver a curriculum that is both comprehensive and policy aligned.

In Italy the variety of projects is visible under different perspectives: e.g., zooming on the University of Insubria activities, to face with the 'plastic problem,' it emerges the importance of working with an interdisciplinary approach as described below.

The ProPla project (funded by Fondazione Cariplo 2022) is coordinated by Prof. Loredano Pollegioni at the University of Insubria. The research team includes experts from seven units specializing in plastic pollution, enzyme engineering, systems biology, microbiology, entomology, economics, and life cycle assessment. The participating institutions include the University of Milan, the University of Milano-Bicocca, and the Water Research Institute – CNR. The project aims to mitigate the environmental and public health impacts caused by improper plastic disposal, inefficient treatment processes, and the uncontrolled release of microPET. The main objective of the project is to develop an innovative biotechnological application for the removal of PET microplastics (microPET) from wastewater (including treatment plants and household sources such as washing machines and tumble dryers), thereby preventing their release into the environment. The recovered microplastics are enzymatically degraded into their monomers, terephthalic acid (TPA) and ethylene glycol, using an engineered PET-degrading enzyme. Subsequently, TPA is converted into D- or L-alanine by a novel engineered *Escherichia coli* strain. Fur-

thermore, by colonizing the microbiota of the insect *Hermetia illucens* with this engineered bacterium, a biological system will be established for the sustainable valorisation of microPET. The goal is to achieve a paradigm shift: transforming an environmental contaminant, potentially harmful to human health, into a valuable resource to produce useful goods, through a fully sustainable and 'green' approach.[2]

The LIFE CASCADE project (LIFE22 ENV, contract no. 101113942), launched on 1 October 2023 and running for 48 months, focuses on the development, testing, and demonstration of innovative technologies for the removal of two classes of emerging contaminants of particular concern to the textile sector: per and polyfluoroalkyl substances (PFAS) and microplastics. The project aims to evaluate analytical procedures and technological solutions at laboratory scale and validate them at pilot scale, both within textile companies and in centralized wastewater treatment plants. By identifying the most effective combination of treatment technologies, LIFE CASCADE seeks to reduce environmental emissions and promote the reuse of treated water in industrial cycles, while assessing the ecotoxicological feasibility of supplying industrial aqueducts. The consortium brings together 14 partners (besides University of Insubria) with complementary expertise in water treatment, environmental research, and textile innovation. Prof. Antonio Di Guardo, coordinates the activities related to PFAS and microplastics, with a focus on analytical detection, environmental fate, and removal strategies. During the project, prof. Roberta Bettinetti and her team developed a high definition optical microscopy protocol for the quantitative evaluation of microplastics in liquid matrices, enabling accurate characterization of particle abundance and typology. Building on the knowledge generated within LIFE CASCADE, the research team is also carrying out a parallel study on microplastic contamination in Lake Como, examining both sediments and, most extensively, the zooplankton community. These insights contribute to improving environmental management strategies in the context of Circular Economy principles and plastic pollution mitigation.[3]

The AWARE project, funded by the Italian Ministry of University and Research (MUR) in the context of the Italian Science Fund (FIS) 2022–2023, coordinated by Dr. Gilberto Binda, researcher at University of In-

[2] More info at https://www.theproteinfactory2.it/propla
[3] More information can be found at https://lifecascade.eu/

subria, investigates how plastics and their biofilms influence nutrients in the water and plankton communities and explores how they change the properties of sediments, affecting exchanges between the bottom (benthic) and the water column (pelagic), as well as energy transfer at their interface. AWARE aims to provide a new perspective on how plastics are becoming a permanent component of aquatic ecosystems, helping us better predict and manage their long-term environmental impacts.[4]

Given the complexity and relevance of the sector's issues, the University of Insubria has established a Sustainable Fashion Research Center. This center serves as a center of excellence dedicated to the development of innovative solutions for the textile and fashion industries, aiming to accelerate the transition to production models based on the circular economy, resource efficiency, and reduced environmental impact. The Center's activities are based on an interdisciplinary approach that integrates scientific research, technological innovation, and economic model analysis, in close collaboration with businesses, institutions, and creative communities. From this perspective, the Center contributes to the construction of a more sustainable, resilient, and competitive textile supply chain. In the activities (research and education) an integrated attention is dedicated to environmental, economic and social aspects.[5]

The activities carried out within these projects and the associated research initiatives are aligned with the broader objectives of EDU4PlastiCircular, as the project is aimed at integrating research, education, and innovation to promote the adoption of Circular Economy strategies for plastic pollution management.

The EDU4PlastiCircular project is a collaborative initiative involving partners from Romania, Slovenia, Italy, and Spain. These organizations have a long history of implementing European-funded projects (primarily Erasmus+, Interreg, and Horizon) focused on environmental sustainability, circular economy, and waste management.

Table 5.2 present a collection of projects (in the field of research and education, with different financial support and different local/regional

[4] Further information on the project is available at https://www.linkedin.com/in/gilberto-binda-41604ab7/

[5] Information on specific projects can be found at https://www.uninsubria.it/ricerca/strutture-la-ricerca/centri-di-ricerca/centro-di-ricerca-sulla-moda-sostenibile

TABLE 5.2 Projects that Extend EDU4 PlastiCircular Initiative (by Partner Institutions)

Project Title	Type	Brief description	Web page
PLAN-C	Interreg Danube	Focusing on transforming the plastics value chain in the Danube region. Partner Politehnica University Timisoara (RO) and ICMPP co-create circular plastics prototypes.	https://keep.eu/projects/29907
MicPlaPROB	Erasmus+	Awareness of microplastics; digital learning; interdisciplinary SI-IT partnership. Coordinator: Dermol Ltd. (SI), Partner: Faculty of Environmental Protection (SI)	https://microplastics.today/
GreenGate	Erasmus+	Responsible use of cosmetics; harmful chemicals, and adult education. Partner: Faculty of Environmental Protection (SI); with the focus on plastic and microplastic ingredients/packaging	https://green-gate.eu/
GreenGate2	Erasmus+	Youth education on health, environment, and responsible consumption. Partner: Faculty of Environmental Protection (SI); with the focus on plastic and microplastic ingredients/packaging	https://green-gate.eu/
PLASTIX	Interreg Europe	Circular economy transition in plastics; policy improvement; SI region included (Faculty of Environmental Protection)	https://www.interregeurope.eu/plastix
FREINDS	Erasmus+	Developed by Dermol Ltd. (SI) and partners from IT and RO, it creates e-learning courses and gamified digital tools for green skills and environmental awareness.	https://dermol.si/category/eu-projects

Continued on the next page

impact) that has been supported by EDU4 PlastiCircular training programme (by developing the green skills and competencies of different teams' members, in different organizations in Europe), focusing on *circularity, plastics, or environmental management and engineering topics,* that have been developed or implemented by these partners.

More recent, EDU4 PlastiCircular initiative has been expand and impact new projects (developed by partners) specifically focused on *Industrial Symbiosis (IS)* and *Urban Symbiosis (US).* These projects empha-

TABLE 5.2 *Continued from the previous page*

Project Title	Type	Brief description	Web page
CircE	Interreg Europe	An Italian-led project (Lombardy Region) involving Spain and Slovenia to improve regional policies for circular economy in sectors like plastics and textiles.	https://interregeurope.eu/circe
DigiFunCollab	Erasmus+	A collaborative project between partners in Italy, Romania, and Slovenia focused on digital transformation and collaborative learning tools for sustainability.	https://digifuncollab.eu
SymbioTech	Erasmus+	A project implemented by Dermol (SI) and Politehnica Timisoara (RO) aimed at technical education in industrial symbiosis and sustainable technology.	https://dermol.si/category/eu-projects
VIRIDI	Interreg SI-AT	Supporting SMES in Slovenia to adopt greener business models, improved recycling practices, and circular digital platforms.	https://interreg.eu/news-stories
BIOECO-UP	EU Project	A project managed at the University of Ljubljana (SI) focusing on the bio-based circular economy and the upscale of bio-economic value chains.	https://bf.uni-lj.si/en/research

size the exchange of waste, energy, and resources between different industries or between urban centres and industrial zones to close loops (Table 5.3).

The new projects presented in Table 5.3 and the related topic of industrial (and urban) symbiosis are new generation extensions of the EDU4PlastiCircular project outcome (supporting its sustainability, too) because of the following arguments:

- Waste as a resource because these projects and initiatives treat plastic not as waste, but as a secondary raw material that can be transferred from an 'exporter' (e.g., a city's urban waste) to an 'importer' (e.g., a plastic manufacturing plant).
- Multidisciplinary training because like EDU4PlastiCircular, these projects require engineers to understand not just chemistry, but also logistics, legislation, and digital tracking (IOT) to manage the flow of materials between partners.

TABLE 5.3 Projects on Industrial and Urban Symbiosis

Project title	No./ID	Brief description	Web page
EcoNexus	PN-IV-P2-2.1-PED-2023	Led by Politehnica University Timisoara (RO), it develops a digital platform to facilitate Industrial Symbiosis. It uses AI and data mapping to connect resource 'waste' from one company to the raw material 'needs' of another.	https://econexus.upt.ro
CORALIS	Horizon 2020	Focuses on creating real-life pathways for Industrial Symbiosis in energy-intensive industries. Partners in Italy and Spain develop 'IS enablers' to monitor resource flows between plants.	https://coralis-h2020.eu
Symbi	Interreg Europe	Improves regional policies to support Industrial Symbiosis. Involves partners from Slovenia (Governmental Office) and Italy to foster resource efficiency in regional ecosystems.	https://interregeurope.eu/symbi
ACCELERE	Erasmus+	A project involving Politehnica University Timisoara (RO) aimed at accelerating the transition to a circular economy through technical training in Industrial Symbiosis for engineers.	https://accelere.upt.ro

Continued on the next page

Regional focus because most of these projects are active in the Italy-Slovenia or Danube (RO) corridors, thus creating a geographic synergy with your current consortium.

Ensuring Long-Term Impact: Establishing the Sustainability of the EDU4PlastiCircular Initiative

Ensuring the long-term sustainability of the EDU4PlastiCircular initiative is a primary objective that is addressed through a multi-layered strategy focusing on institutionalization, pedagogical innovation, and digital permanence. The most significant pillar of this strategy is the institutionalization of project outputs within the permanent curricula of the partner universities. Rather than remaining as a standalone project, the EDU4PlastiCircular modules on sustainable plastic management are being integrated into the core engineering and environmental science programs at UPT, UPV, UNITBV, and the University of Insubria. This integration is supported by the development of spe-

TABLE 5.3 *Continued from the previous page*

Project title	No./ID	Brief description	Web page
SCALER	Horizon 2020	Scaling European Resources with Industrial Symbiosis. It provides a blueprint for European regions (including Spain and Italy) to identify synergy opportunities between diverse industrial sectors.	https://scalerproject.eu
URBANREC	Horizon 2020	A major Urban Symbiosis project led by AIMPLAS (ES). It focuses on the recovery of bulky waste from cities (mattresses, furniture) and converting them into high-value chemicals and fuels.	https://urbanrec-project.eu
T-REX	Horizon Europe	Focuses on the Urban-Industrial nexus for textile recycling. Involves collecting post-consumer urban waste to feed back into industrial manufacturing cycles in Italy and Spain.	https://trex-project.eu
REMADE	Interreg Italy-Slovenia	Promotes the use of recycled materials in the construction sector through Urban Symbiosis, using waste from Slovenian and Italian demolition sites as 'new' raw materials.	https://ita-slo.eu/remade

cialized Training Personas and a comprehensive Syllabus, ensuring that the learning objectives are aligned with the specific needs of students at the Bachelor's, Master's, and PhD levels. The Handbook for Trainers, available in multiple European languages, further facilitates this process by providing local faculty with the tools and methodologies needed to deliver the content long after the project's formal conclusion.

The sustainability of the initiative is further bolstered by its commitment to digital permanence and open access. The Digital Library and E-learning platform serve as persistent resources that remain accessible to the global academic and professional community. By utilizing Digital Badges and certificates, the project provides a recognized framework for the validation of green skills, encouraging lifelong learning and continuous engagement with the project's materials. Additionally, the creation of a 'Circular Economy Community' through Multiplier Events and Action Labs ensures that the collaborative networks established during the project continue to thrive. These events engage a wide range

of stakeholders, including SMES, NGOS, and local authorities, creating a feedback loop where academic research informs industrial practice and societal needs. This community-based approach ensures that the spirit of EDU4PlastiCircular remains a driving force for regional and European innovation in the circular economy for years to come.

Acknowledgments

The ideas developed in this chapter are based on the authors' earlier publications reflecting the collaborative work of them in the EDU4PlastiCircular project. This material has been substantially revised, updated and extended to align with the core themes of the current volume. Thus, the chapter represents a conceptual evolution of our previous studies:

Dermol, Š., & Dermol, V. (2024). Exploring online education for circular economy: Content analysis and didactical approaches in plastic waste management courses. *International Journal of Management, Knowledge and Learning, 13,* 209–222.

Draghici, A., Boatca, M. E., Rada, E. C., Perniu, D., Bubik, A., Baera, C., & Sirbu, R. M. (2024). Education for plastic in a circular and climate neutral economy: Preventing waste ending up into the environment. *Acta Technica Napocensis, Series: Applied Mathematics, Mechanics, and Engineering, 67*(Special Issue III), 1105–1114.

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Giurea, R., Tulbure, A., Popescu, L. G., Adami, L., Ragazzi, M., & Rada, E. C. (2025). Fostering sustainability: Integrating circular economy practices to manage plastic waste in universities. *Journal of Physics: Conference Series, 3028*(1), 012018.

Komerički Kotnik, L., Školnik Škrabe, K., & Bubik, A. (2025). Erasmus+ projects as the opportunity to improve youth awareness on microplastics. In *Proceedings of the Conference Politechnica* (pp. 183–188). The Academy of Applied Studies Polytechnic.

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Chapter Six

Conclusions

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https://doi.org/10.53615/978-83-65020-56-7/199-206

Key Messages

The increasing scale and complexity of plastic pollution, particularly the proliferation of micro- and nanoplastics, represent one of the most pressing environmental challenges of the 21st century. As highlighted throughout this book, the persistence of plastics in terrestrial and aquatic ecosystems, combined with their entry into food chains and potential impacts on human health, underscores the urgency of systemic change (Geyer et al., 2017; United Nations Environment Programme, 2021). Addressing this challenge requires not only technological innovation and regulatory frameworks, but also a profound transformation in knowledge, values, and behaviours across society. In this regard, education emerges as a critical driver of the transition toward a circular and climate-neutral economy (Calleja, 2019; Giurea et al., 2024; Draghici et al., 2024).

The evidence presented in this volume confirms that the current linear 'take-make-waste' model of plastic production and consump-

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

tion is inherently unsustainable. The exponential growth in plastic production, coupled with low recycling rates and high material value loss, reveals systemic inefficiencies that contribute to environmental degradation and economic loss (Davis, 2022; Islam, 2025). Despite policy efforts such as the European Green Deal, the circular material use rate for plastics remains low, and significant quantities of plastic waste continue to be landfilled, incinerated, or leaked into the environment (Mulita, 2023). These findings reinforce the need for a transition toward circular systems that prioritize prevention, reuse, recycling, and sustainable design.

A central conclusion of this book is that such a transition cannot be achieved without rethinking education. Traditional, knowledge-transmission models of teaching are insufficient for addressing complex, interdisciplinary challenges such as plastic circularity. Instead, effective education must adopt transformative, experiential, and systems-oriented approaches that enable learners to critically engage with real-world problems and develop actionable competencies (Dermol & Dermol, 2024; Hamid et al., 2024). Transformative learning, in particular, plays a crucial role in fostering critical reflection and shifting deeply embedded assumptions about consumption, resource use, and environmental responsibility (Mezirow, 1991, 2000; Taylor, 2007).

Experiential and hands-on learning approaches have proven especially effective in enhancing understanding and promoting behavioural change. Activities such as waste audits, recycling projects, and design of products from recycled materials enable learners to connect theoretical knowledge with practical applications (Kolb, 1984; Kolb & Kolb, 2005; Nguyen, 2023). Similarly, citizen science initiatives have demonstrated strong potential for increasing scientific literacy and environmental awareness, particularly in relation to microplastics pollution, by engaging learners directly in data collection and analysis (Popa et al., 2022; Školnik Škrabe et al., 2025).

The integration of digital technologies into education represents another key dimension of this transformation. Digital platforms, e-learning environments, and open educational resources provide opportunities for flexible, scalable, and inclusive learning (Means et al., 2014; Laurillard, 2012). The EDU4PlastiCircular project exemplifies how digital tools can support knowledge dissemination and capacity-building across diverse contexts. However, the findings also indicate that digital learning is most effective when combined with interactive,

collaborative, and experiential elements, suggesting that hybrid learning models offer the greatest potential for impact (Dermol & Dermol, 2024; Draghici et al., 2024).

Another important conclusion relates to the diversity of educational contexts and target groups. Effective circular economy education must be tailored to different audiences, including students in primary, secondary, and higher education, as well as professionals, policymakers, and community members. Higher education institutions, in particular, play a pivotal role as hubs of knowledge creation, innovation, and capacity-building. They are uniquely positioned to integrate circular economy principles into curricula, foster interdisciplinary collaboration, and act as 'living laboratories' for sustainable practices (Bugallo-Rodríguez et al., 2020; Giurea et al., 2024).

At the same time, the book highlights the importance of community-based and informal education in reaching broader audiences and promoting behavioural change at the societal level. Initiatives that engage local communities, encourage participation, and connect learning with real-life challenges have demonstrated significant potential for fostering environmental responsibility and collective action (Widiastuti et al., 2023; Velis et al., 2022). International and cross-cultural collaboration further enhances these efforts by enabling knowledge exchange and adaptation of best practices across different contexts (Kruja et al., 2025).

Despite these promising developments, substantial challenges remain. Institutional barriers, including rigid curricula, disciplinary silos, and limited incentives for pedagogical innovation, continue to constrain the integration of circular economy education (Giurea et al., 2025; Stathatou et al., 2025). In addition, gaps in educator knowledge and competencies, insufficient resources, and limited infrastructure hinder the implementation of effective educational initiatives (Školnik Škrabe et al., 2025; Dermol & Dermol, 2024). Addressing these challenges requires coordinated efforts at institutional, national, and international levels, supported by appropriate policy frameworks and funding mechanisms.

The findings also reveal a critical need for more robust evaluation of educational interventions. While many initiatives report positive outcomes in terms of knowledge and attitudes, there is limited evidence regarding long-term behavioural change and environmental impact. Future research should therefore focus on longitudinal studies, the de-

velopment of standardized assessment tools, and the measurement of real-world outcomes (Hamid et al., 2024; Dermol & Dermol, 2024).

From a policy perspective, the transition toward a circular economy must be supported by comprehensive educational strategies. This includes integrating circular economy principles into curricula at all levels, investing in teacher training and professional development, and promoting interdisciplinary and experiential learning approaches. Policies should also encourage collaboration between educational institutions, industry, and communities, recognizing that circular economy requires coordinated action across sectors (Mulita, 2023; Draghici et al., 2024).

In conclusion, this book demonstrates that education is not merely a supportive element of the circular economy transition-it is a foundational pillar. By equipping learners with the knowledge, skills, and values necessary to understand and address complex sustainability challenges, education can drive systemic change and support the development of more resilient and sustainable societies. The EDU4PlastiCircular project provides a valuable model for how such education can be designed and implemented, combining innovative pedagogy, digital tools, and international collaboration.

Ultimately, achieving a circular and climate-neutral future depends on our collective ability to rethink existing systems and embrace new ways of learning and acting. This requires not only institutional and technological innovation but also a cultural shift toward sustainability and responsibility. The insights presented in this volume offer both a critical reflection on current practices and a forward-looking vision for the role of education in shaping a more sustainable world.

Limitations and Future Research

Despite the comprehensive scope of this book and the valuable insights generated through the EDU4PlastiCircular project, several limitations should be acknowledged.

First, the analysis of educational initiatives in circular economy and plastic circularity is largely based on existing literature and project-based evidence. While this provides a broad and structured understanding of current practices, it may not fully capture the diversity of informal, emerging, or non-documented educational approaches, particularly those developed in less-researched regions or outside formal institutional settings. Additionally, the majority of the reviewed studies

focus on short-term outcomes, such as increased knowledge or awareness, while longitudinal evidence on sustained behavioural change and real environmental impact remains limited.

Second, the empirical insights derived from the EDU4PlastiCircular project are context-dependent. The project is primarily rooted in European higher education systems and reflects specific institutional, cultural, and policy environments. As a result, the transferability of findings to other geographical or socio-economic contexts (especially low- and middle-income countries) may require careful adaptation. Differences in infrastructure, access to digital technologies, and educational traditions can significantly influence the effectiveness of proposed pedagogical approaches.

Third, while the book highlights the role of digital tools and e-learning environments, the evaluation of these tools is constrained by user preferences and implementation variability. Evidence suggests that digital learning, although scalable and flexible, is not always the most engaging format for learners when used in isolation. The lack of standardized evaluation frameworks for digital and hybrid learning in circular economy education also limits the comparability of results across initiatives.

Fourth, the interdisciplinary nature of circular economy education presents methodological and practical challenges. Integrating knowledge from engineering, environmental science, economics, and social sciences requires coordinated curriculum design and collaboration among educators, which is often difficult to achieve within existing institutional structures. This complexity may have limited the depth of analysis in certain thematic areas.

Looking ahead, several directions for future research can be identified.

There is a clear need for longitudinal studies that assess the long-term impact of educational interventions on behaviour, professional practices, and environmental outcomes. Such research would provide stronger evidence on the effectiveness of circular economy education in driving systemic change.

Future research should also focus on the development of standardized assessment frameworks for measuring competencies related to circular economy and sustainability. This includes not only cognitive knowledge but also skills, attitudes, and behavioural intentions.

Another important avenue is the exploration of hybrid pedagogical

models that effectively combine digital and experiential learning. Investigating how digital tools can support hands-on activities, collaboration, and real-world problem-solving will be critical for enhancing learning outcomes.

Further studies are needed to examine context-specific adaptations of circular economy education, particularly in diverse cultural and socio-economic settings. Comparative research across regions can help identify best practices and support the development of globally relevant yet locally adaptable educational strategies.

In addition, future work should explore the role of industry partnerships and stakeholder engagement in education. Strengthening collaboration between academia, industry, and communities can enhance the relevance and practical impact of educational initiatives.

Finally, the integration of circular economy principles into formal curricula and policy frameworks warrants deeper investigation. Research on institutional change, governance mechanisms, and policy support can provide valuable insights into how educational systems can more effectively contribute to the transition toward a circular and climate-neutral economy.

In conclusion, while this book provides a solid foundation for understanding and advancing education for plastic circularity, it also highlights the need for continued research, innovation, and collaboration. Addressing these limitations and pursuing the identified research directions will be essential for strengthening the role of education as a driver of sustainable transformation.

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Reviews

This monograph presents a comprehensive and innovative examination of education in the context of circular economy and plastic waste prevention. Its interdisciplinary nature is a key strength, as it integrates environmental, technological, and pedagogical perspectives into a coherent framework. The focus on digitalisation as an enabler of education for sustainability adds a contemporary and forward-looking dimension to the work.

The monograph's originality lies in its ability to combine theoretical foundations with practical applications. The authors not only review existing literature but also propose concrete educational approaches and tools that can be implemented in higher education and beyond. The emphasis on digital learning environments, open educational resources, and innovative teaching methods highlights the evolving role of education in addressing complex environmental challenges. The scientific relevance of the work is further reinforced by its alignment with current research trends and policy priorities. The monograph contributes to the development of knowledge in education for sustainable development and provides a valuable resource for both academic and professional audiences. The analytical depth of the literature review is commendable. The authors demonstrate a thorough understanding of the field and critically engage with existing studies. The synthesis of findings is clear and leads to meaningful conclusions and recommendations. The structure of the monograph supports a logical progression from theoretical background to practical implications. In terms of applicability, the monograph has significant potential to influence educational practice and policy. It offers guidance for curriculum development, supports interdisciplinary teaching, and promotes the integration of sustainability into higher education. The international perspective of the work further enhances its relevance and transferability across different contexts.

Overall, the monograph is a well-developed, scientifically grounded, and highly relevant contribution to the field. It addresses an important topic with clarity and depth, offering both conceptual insights and practical value.

Dr. Jaka Vadnjal

Dermol, V., Draghici, A., Perniu, D., Bubik, A., Rada, E. C., & Ferrándiz Bou, S. (Eds.) (2026). *The Digital Frontier of Circularity.* ToKnowPress.

The monograph addresses a highly relevant and timely topic situated at the intersection of environmental sustainability, circular economy, and education. The issue of plastic waste, including micro- and nanoplastics, represents one of the most pressing global environmental challenges. The authors convincingly position education as a key driver of systemic change, aligning well with contemporary international policy frameworks such as the European Green Deal and global sustainability agendas.

The monograph's scientific contribution lies in its interdisciplinary approach, combining insights from pedagogy, the environmental sciences, and digital learning. The work provides a comprehensive synthesis of existing research through an extensive literature review and offers a structured overview of contemporary educational approaches to circular economy and plastic waste management. In particular, the discussion of experiential learning, participatory methods, digital platforms, and gamification demonstrates both theoretical depth and practical relevance. Methodologically, the monograph is sound and well-structured. The literature review draws on a broad, relevant body of academic sources, enabling a coherent comparative analysis and well-founded conclusions. The organisation of the chapters is logical, and the narrative flow supports a clear understanding of the research context and findings. The monograph's language is appropriate for an international academic audience. The text is clearly written, coherent, and professionally presented. The structure of the work enables both theoretical insight and practical application, making it accessible to researchers, educators, and practitioners.

The monograph's societal and practical impact is particularly noteworthy. The work contributes to curricula development, supports the acquisition of green competences, and provides guidance for higher education institutions seeking to integrate circular economy principles into teaching and learning. The inclusion of digital tools and open educational resources further enhances its applicability.

The monograph represents a high-quality scientific contribution that is both relevant and impactful. It successfully bridges theory and practice, offering valuable insights into education for the circular economy and sustainability.

Dr. Suzana Košir

Plastic pollution is one of the most pressing environmental challenges of our time. Addressing it requires more than technological solutions; it demands new knowledge, skills, and educational approaches.

Developed within the European EDU4PlastiCircular project, this book offers a comprehensive, practical resource for higher education teachers, researchers, students, and sustainability professionals. It explores the challenges of preventing plastic waste, microplastics, innovative materials, and the transition to a circular, climate-neutral economy. Particular attention is given to innovative teaching approaches, digital learning environments, interactive educational tools, and the development of green competencies. The book also presents the EDU4PlastiCircular training and certification framework, digital resources, and examples of European collaboration supporting sustainability education.

By combining scientific insights with educational practice, the book offers guidance on integrating plastic circularity into higher education and promoting interdisciplinary learning. More than a collection of research findings, it is a starter kit designed to inspire educators, strengthen sustainability competencies, and encourage practical action towards responsible plastic production, consumption, and waste management. It invites readers to rethink how education can contribute to a sustainable circular future.

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