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.

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

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

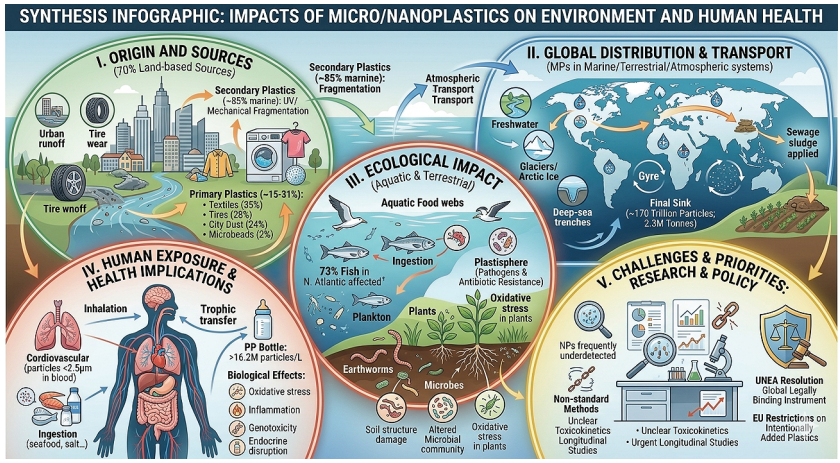


FIGURE 3.2 Micro/Nanoplastics Impacts and Challenges (Developed Using Gemini AI Application)

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)

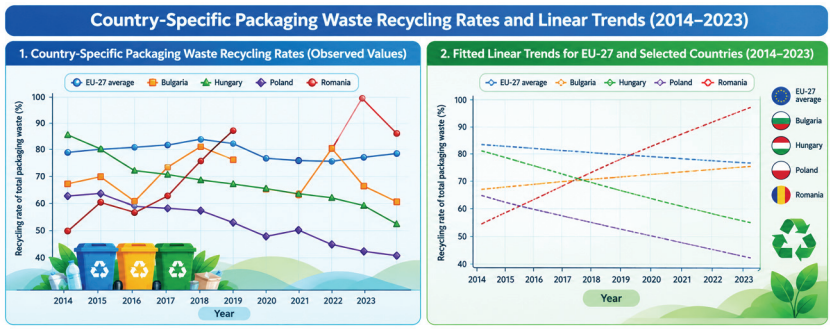


FIGURE 3.4 Country-Specific Observed Series

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.

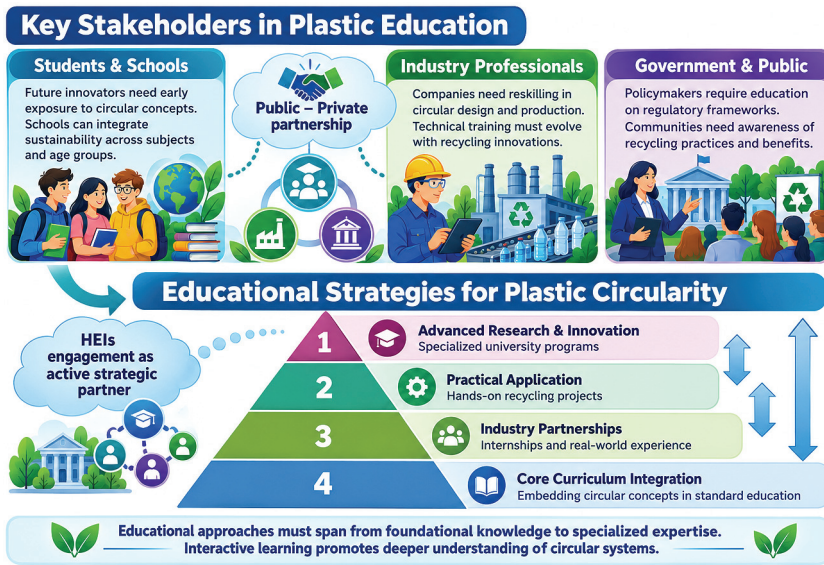


FIGURE 3.6 The Proposed Synthesis of the Education Approach for Plastic Circularity and Circular Economy

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*

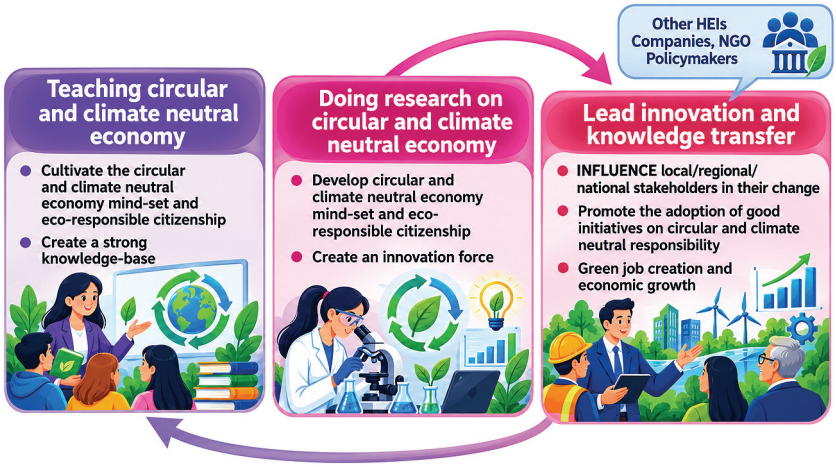


FIGURE 3.7 The Role of HEIS in Supporting the Real Transition to the Circular and Climate Neutral Economy

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/

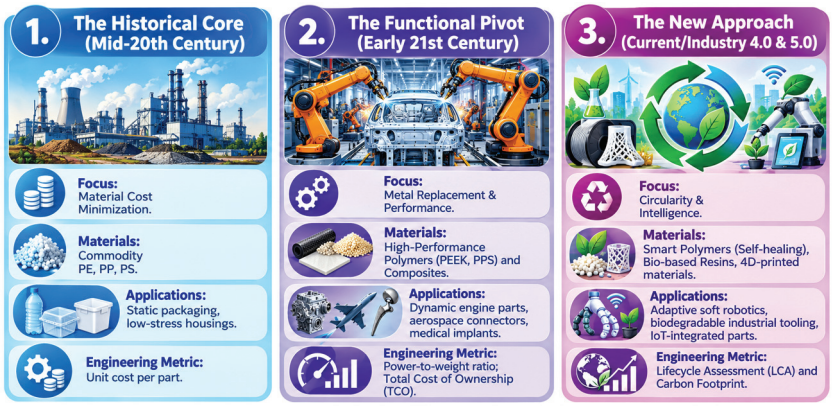


FIGURE 3.8 The Industrial Polymer Evolution Model

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

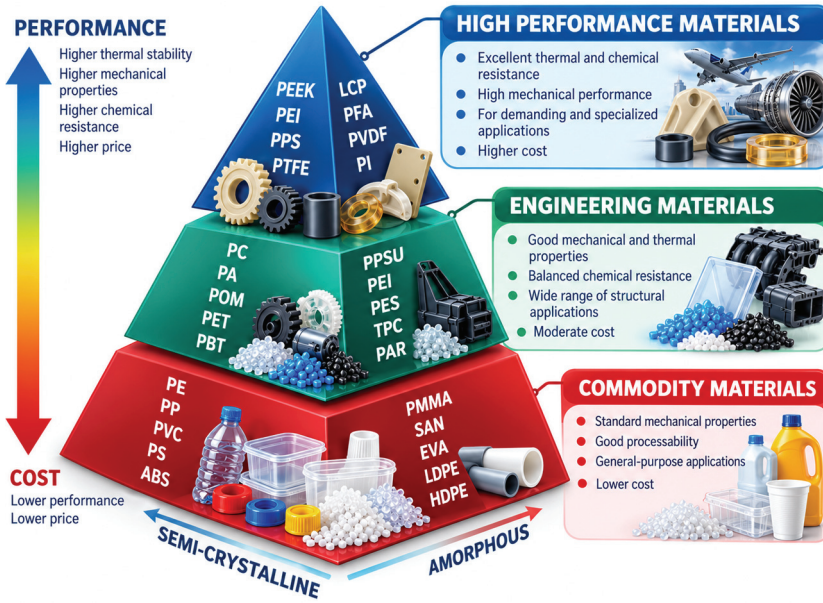


FIGURE 3.9 Example of Polymer Pyramids

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.*

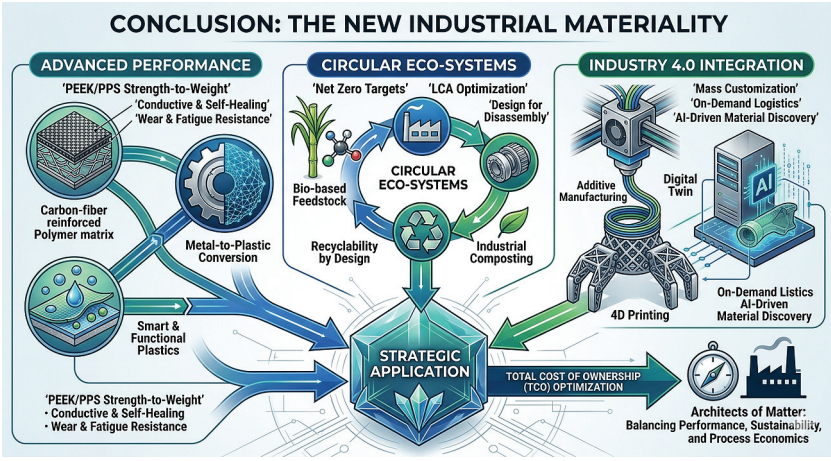


FIGURE 3.10 The New Industrial Materiality

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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