Tampere University of Applied Sciences

Circular Initiatives for the European Coating Industry

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ABSTRACT

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This thesis investigates the integration of Circular Economy (CE) principles within the European Coating Industry (ECI), highlighting the necessity for a shift towards sustainable practices driven by environmental concerns and regulatory demands. The research aimed to identify the challenges and strategies necessary for transitioning from traditional linear production to sustainable, circular processes, with a focus on resource efficiency, material reuse, and closed-loop systems. Methods employed included a combination of qualitative and quantitative approaches, such as case studies, literature reviews, and analyses of industry reports, to provide a comprehensive understanding of how different-sized companies within the ECI implement CE principles under strict environmental standards.

The results revealed that while large companies displayed robust CE strategies aimed at reducing waste and enhancing resource efficiency, smaller companies contributed significantly to circularity through innovative raw material usage tailored to specific product lines. However, these smaller companies faced substantial challenges in scaling and commercializing their innovations, underscoring the need for enhanced collaboration across the industry. This varied implementation of CE principles across companies of different sizes illustrated the complexities and nuances of adopting sustainable practices within the ECI.

The thesis concludes that for the ECI to fully embrace CE principles, alignment with regulatory frameworks and prioritization of resource efficiency are crucial. Moreover, the industry must proactively respond to new regulations targeting persistent environmental pollutants, such as "forever chemicals", refers to per- and polyfluoroalkyl substances (PFAS), a group of man-made chemicals that are extremely persistent in the environment and human body, meaning they don't break down and can accumulate over time. The study suggests that advancing sustainability in the coating industry requires collaborative efforts between companies, research institutions, and policymakers. Recommendations for further development include enhancing transparency in company practices and increasing government incentives to foster broader adoption of CE principles, thereby ensuring a more sustainable and resilient future for the European Coating Industry.

Keywords: Circular Economy, European Coating Industry, Sustainability, Business Scale, Regulatory Compliance

CONTENTS

GLOSSARY

CE	Circular Economy
ECI	European Coating Industry
EU	European Union
VOC	Volatile organic compound
PFAS	Per- and polyfluoroalkyl substances
KPI	Key performance indicators
REACH	Registration, Evaluation, Authorisation, and Restriction of Chemicals
LCA	Life Cycle Analysis
UV	Ultraviolet
GHG	Greenhouse Gas
CO_2	Carbon dioxide
IP	Intellectual property
TBL	Triple bottom line

1 INTRODUCTION

This thesis aims to provide readers with a detailed understanding of key concepts and their implications within the Circular Economy (CE) framework, specifically applied to the European Coating Industry (ECI). The purpose is to elucidate current practices and technologies used in the industry, examining their impact on the environment and compliance with regulatory standards. The research goal is to enhance awareness of the industry's practices, emphasizing to a wider audience the essential role of circularity as a fundamental element for the sustainable advancement of the European coating sector. This research delves into the significance of adopting circular and sustainable practices, providing a basis for evaluating effective strategies, solutions, and policy recommendations that promote circular business initiatives. By the end of this thesis, readers will have a thorough understanding of the CE principles among coating sectors and how they can be applied to guide the ECI towards a greener and more sustainable future.

1.1 Current practices in the coating industry in Europe

The ECI is a vital sector within the region's chemical and manufacturing landscape. It encompasses the production of paints, varnishes, and specialty coatings, serving diverse applications such as automotive, construction, aerospace, and industrial equipment.

Despite the growing significance of economically viable, socially responsible, and environmentally friendly sustainability practices within the ECI, it is crucial to recognise that not all companies prioritise sustainability or not yet implement any circular approach. For example, many coating companies are still using solvent based coating which is not environment friendly despite the shift towards water-based coatings.[1] Solvent-based coatings contain higher levels of volatile organic compounds (VOCs) that contribute to air and water pollution and pose health risks to workers and the environment.[2] Besides, not all coating manufacturers in the EU have implemented comprehensive recycling and waste management practices. Some may still dispose of coating residues, packaging materials, and hazardous waste through conventional means, such as landfilling or incineration, rather than exploring recycling or reusing options.[3]

It is also crucial for coating industry to adopt energy-efficient coating technologies while some manufacturers continue to use outdated equipment or inefficient processes that result in higher energy consumption and increased carbon emissions.[4] Despite EU's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulations[5] aim to promote the substitution of hazardous chemicals, not all coating companies proactively seek alternatives. Some manufacturers may still utilise chemicals that pose risks to human health and the environment without actively exploring safer alternatives. Some coating companies in the EU may not prioritise transparency and data sharing due to intellectual property (IP) concern. This means they may not provide detailed information on the environmental impact of their coatings, making it challenging for customers to make informed decisions based on sustainability criteria.[6]

Furthermore, collaboration and industry initiatives between stakeholders are crucial drivers of sustainability, not all coating companies actively participate in such endeavours. Some manufacturers may operate independently, without engaging in knowledge-sharing, industry associations, or collaborative projects aimed at improving sustainability practices.[7]

1.2 Impact of coating industry on the environment

The coating industry is a critical component of various sectors, including manufacturing, construction, automotive, and aerospace, providing protection, aesthetics, and functional properties to an extensive range of products and surfaces. While coatings are essential for enhancing durability and appearance, their production and application can have significant environmental repercussions.

One of the most significant environmental challenges posed by the coating industry is the emission of volatile materials. VOCs are commonly found in coatings as solvents, and their release during the drying and curing processes of coatings contributes to air pollution. Regulatory agencies worldwide have implemented stringent limits on VOC emissions from coatings to mitigate their environmental impact.[8]

High-quality coatings often demand substantial amounts of raw materials, including petroleum-based solvents and pigments. The extraction and processing of these materials can lead to environmental degradation, including habitat destruction and pollution. These resource-intensive processes contribute to greenhouse gas emissions and exacerbate the depletion of non-renewable resources.[9]

The coating industries also generate substantial amounts of hazardous and non-hazardous waste. The disposal of waste materials, such as unused coatings, solvents, and contaminated equipment poses significant challenges. Some coatings contain toxic heavy metals, such as cobalt, lead and chromium, which can leach into soil and water if not managed properly. The wastewater generated during the production and application of coatings may contain harmful chemicals, heavy metals, and VOCs. Without proper treatment, these pollutants can contaminate aquatic ecosystems and harm aquatic life.[10]

Additionally, per- and polyfluoroalkyl substances (PFASs), consisting of a chain of carbon and fluorine atoms are valued for their unique properties but are notorious for their persistent environmental presence. These chemicals are often referred to as "forever chemicals" due to their persistence and inability to degrade naturally. The use of PFASs is extensive in Europe, particularly in applications such as powder coatings, UV curing coatings, anti-reflective coatings, and coatings for cables, wiring, and solar panels.[11] [12,13] *Le Monde* and the “Forever Pollution” Project[14] reveal the magnitude of the contamination of the European continent. Across Europe, thousands of sites are contaminated as depicted in the Figure 1. These "forever chemicals" can travel significant distances from their point of release, presenting formidable challenges for environmental management. A detailed family tree of PFAS chemicals can be found in Appendix 1.[15]

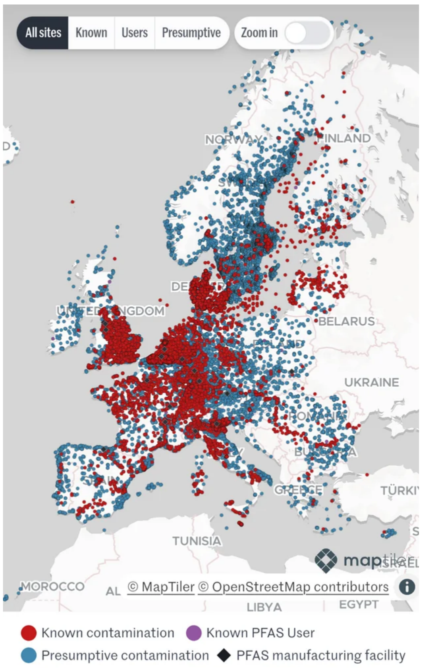

Figure 1: Europe contamination by "Forever Chemicals"[14]

Researchers and industry professionals have recognised the urgency of addressing these issues through innovations in coating technology, including the development of low-VOC[16],eco-friendly coatings,[17] alternative curing methods,[18] and improved waste management practices.[19] Rooted in green chemistry principles since 1998, the industry's sustainability paradigm aims for zero harm to health and the environment meaning zero VOC, zero waste, and net-zero emissions in the coatings industry.[20] Efforts to diminish the environmental footprint of the coating industry are crucial for promoting a more sustainable future.

1.3 Research objectives and scope

This research aims to provide a thorough understanding of the integration of CE principles in the coating business strategy, with a specific focus on circularity within the ECI. The coating industry faces challenges concerning resource scarcity, waste generation, and environmental repercussions.[21] The research assesses the current state of the circular initiatives in the ECI, identifying barriers and opportunities for implementing CE and sustainability practices. The overarching goal is to contribute to the industry's long-term circular initiatives while fostering innovation and sustainability through research and development aligned with

EU regulatory requirements.[22] This thesis specifically concentrates on environmental considerations, highlighting the importance of sustainable sourcing of raw materials, minimizing resource usage and waste generation, and to explore the new innovation technologies used in coating sectors to improve the strategy towards circularity of current products. The study delves into the challenges of adopting CE practices across businesses of varying sizes, from multinational giants to smaller firms, assessing how the scale of a company affects its ability to implement these practices and comply with EU directives. By exploring these dynamics, the research intends to uncover effective strategies for circularity that not only contribute to sustainable development but also improve the environmental impact of the industry. This investigation will provide valuable insights into fostering sustainable growth through circular economy strategies tailored to different business scales.

Research questions

Derived from the research objectives, the following specific research questions (RQs) aim to guide the investigation into the circular practices within the ECI:

RQ1: How are CE principles currently integrated across different scales of enterprises within the ECI?
This question explores the extent and effectiveness of CE practices among various companies, focusing on how business size and scope influence the integration of sustainable practices.

RQ2: What are the key environmental impacts and challenges associated with the linear production model in the coating industry?
This question aims to identify the environmental burdens specific to the traditional "take-make-dispose" model in the coating industry, including the production of waste, use of non-renewable resources, and emission of pollutants.

RQ3: What opportunities exist for enhancing CE practices in the coating industry, and what are the best practices for their implementation?

Focusing on innovative solutions, this question seeks to discover opportunities for reducing environmental impacts through CE practices such as waste reduction, coating process optimization, and the use of renewable resources.

RQ4: What recommendations can be made to policymakers, coating companies, and industry stakeholders to facilitate the transition towards a more sustainable and circular coating industry?
This question aims to outline actionable strategies and policy recommendations that support the adoption of CE principles, focusing on regulatory frameworks, incentives for sustainable practices, and collaborative initiatives within the industry.

These research questions are designed to be addressed through empirical and literature studies, contributing directly to the overall research objectives by highlighting practical and theoretical approaches to advancing sustainability in the ECI sector.

1.4 Overview of the structure of the thesis

The structure is organised into six main chapters (including this one), each addressing specific aspects of the research:

- **Chapter 2:** Chapter 2 delves into various aspects of CE, starting with an exploration of its key principles. It then discusses the adoption of CE principles in the coating sector. The chapter provides insights into the current regulatory framework which is aligned with EU coating industry. Additionally, it examines the emergence of “forever chemicals” free sustainable coatings and evaluates CE initiatives within the European innovation policy. The chapter concludes with circularity-related challenges specific to the coating industry, shedding light on pertinent issues faced in transitioning towards a more sustainable and circular future.
- **Chapter 3:** Research Methodology and Approach. This chapter outlines the research methodology employed throughout the study. The explanation of the research approach will be discussed by following standard research methodology approaches. The methods of data collection, analysing the case

studies along with the rationale for selecting candidate data sources will be elucidated.

- **Chapter 4:** Chapter 4 delves into case studies, presenting the key findings of this thesis. Initially, it examines successful CE implementation within the coating industry, followed by an analysis of strategies, challenges, and outcomes. The chapter also explores the diverse approaches to circular initiatives across companies of different sizes, highlighting the economic and environmental benefits of circularity while addressing encountered barriers and challenges.
- **Chapter 5:** Chapter 5 provides an in-depth analysis of how CE principles are integrated within the ECI. It highlights the efforts in adopting CE practices within large to small enterprises to enhance circular approaches through innovative strategies and technologies. The chapter discusses the challenges posed by traditional linear production towards more sustainable practices.
- **Chapter 6:** Conclusion and recommendation. This chapter provides practical recommendations aimed at reshaping circular business practices within the coating industry, emphasizing effective strategies to overcome challenges and bolster sustainability efforts. The discussion extends to highlight crucial future directions for achieving a more sustainable coating industry, identifying emerging trends, innovative technologies, and collaborative pathways to advance sustainability objectives in the field. This chapter serves as a holistic synthesis, offering a roadmap for industry stakeholders to navigate challenges, capitalize on lessons learned, and strategically reshape their approach toward a more sustainable and circular future.

2 LITERATURE REVIEW

This chapter aims to elaborate a comprehensive understanding the current practice and challenge of CE concept in the ECI. Through a meticulous exploration of a variety of academic and industry sources, this chapter will elucidate the fundamental principles of the CE, shedding light on its adoption within industrial settings and the current regulatory framework governing the ECI and its alignment with CE objectives. The chapter will also delve into the European innovation policy and the initiatives aimed at fostering circularity, culminating in a nuanced analysis of the specific challenges that the coating industry faces on its path towards circularity. This chapter also seeks to synthesise a wealth of knowledge and insights from academic research, industry practices, and regulatory documents to aim to educate the reader on the challenges, opportunities, and policy considerations surrounding circularity in this specific sector, ultimately paving the way for a deeper exploration of sustainable solutions and policy recommendations.

2.1 CE concept and its key principles

The CE is based on three principles:

(a) Eliminate waste and pollution.
(b) Circulate products and materials (at their highest value); and
(c) Regenerate nature.

The butterfly diagram depicted in Figure 2 by the Ellen MacArthur Foundation illustrates two primary cycles: the technical cycle and the biological cycle. Within the technical cycle, the emphasis lies on reuse in overall process, while the biological cycle focuses on the return of biodegradable materials to the Earth to facilitate the regeneration of nature.[23]

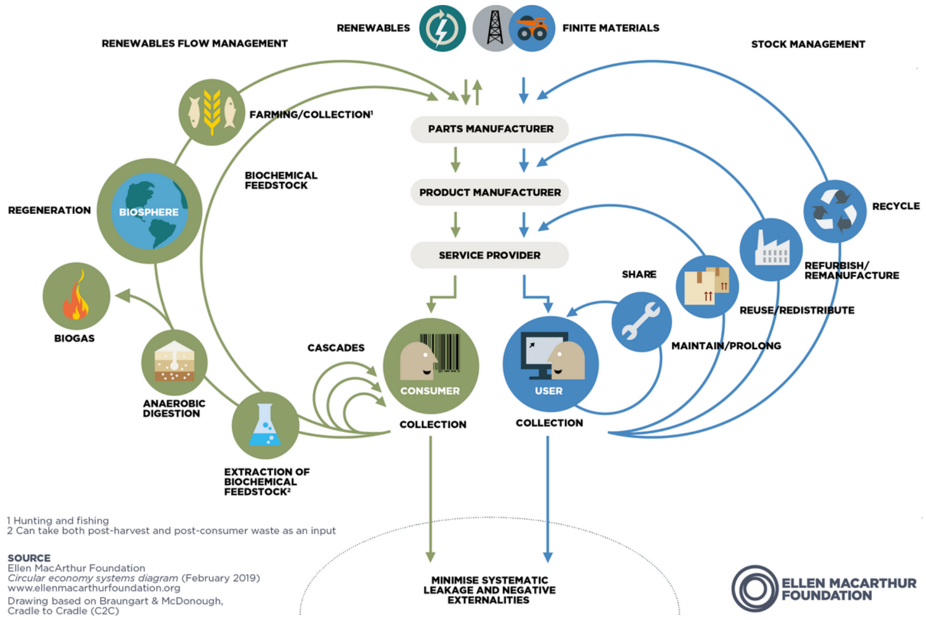

Figure 2. The butterfly diagram illustrates technical and biological cycles.[23]

The first principle of the CE is to eliminate waste and pollution. Achieving a CE, characterized by the elimination of waste and pollution, has become a paramount global goal to address environmental challenges and promote sustainable development. To eliminate waste and pollution, it is necessary to reorganize the entire approach from initiation, implementation, production and finally consumption rather than minimize waste from existing process parameters. To achieve this, it is important to rethink how products are designed, produced, used, and disposed of by potential change in the circular business models, such as remanufacturing and product-as-a-service, to minimize resource consumption and environmental impact. By shifting from a linear "take-make-dispose" model to one focused on preserving and extending the value of products and materials can drastically reduce waste and pollution according to Ken Webster's work[24] where the author has explored the role of innovation, policy, and collaboration during transformation. The first principle also emphasizes the importance of product design that prioritizes biodegradability and safe materials. Biodegradability refers to the ability of a material to decompose naturally in the environment, typically by bacteria or other microorganisms, without causing harm. Safe materials are those that do not pose risks to human health or the environment during their use or disposal.[25]

The second principle is circulating products and materials which is aligned with the idea that resources should be used more efficiently and sustainably. This involves maintaining materials in active use, either as a product, components, or alternative raw materials. This approach ensures inherent value of products and materials.[23] By adopting a circular approach and maintaining the value of products and materials through effective circulation businesses can reduce costs, enhance competitiveness, and create new revenue streams.[26] Furthermore, extending the life of products and materials through efficient circulation (by reusing and recycling materials) can significantly reduce carbon footprint associated with production and disposal.[27]

The third principle of the CE ‘regenerating natural systems and resources’ striving to restore and enhance the planet's ecological health. This principle aligns closely with the broader sustainability agenda and recognizes the intrinsic value of Earth's ecosystems.[23] To effectively implement the third principle, a multitude of methodologies have been proposed and practiced. Implementing agroforestry systems, practicing rotational grassing, and adopting organic farming methods can promote nature regeneration by restoring biodiversity, improving soil health, and reducing environmental impact and, therefore, positively impacting the environment. Many of the raw materials for coating products initially come from the earth for example petroleum for plastic production. When these man-made materials were designed within the CE loop and support regenerative practices, the natural resources will slowly regenerate over time. That’s how circular design thinking and eco-friendly manufacturing processes play pivotal roles in reducing resource consumption and waste generation.[28]

2.2 Circular economy in the european coating industry: necessity and strategies

The ECI, a pivotal sector of the global manufacturing arena, is increasingly facing scrutiny due to its intensive use of resources and significant contributions to waste generation. Hina et al.'s[29] study identifies five levels of CE adoption within manufacturing firms, revealing that most companies have a low integration of CE principles. Traditional production models, characterized by a linear "take-make-dispose" approach, are becoming unsustainable due to limited resources, and rising environmental concerns. In response, the CE initiatives have been adopted as an innovative strategy to uncouple economic growth from resource consumption. This strategy promotes enhance resource efficiency, the reuse of materials, and the establishment of closed-loop systems, all aimed at reducing environmental impacts while fostering economic growth.[30]

At the heart of the CE philosophy in coatings lies cleaner production and resource efficiency. This includes implementing efficient technologies that not only curb pollution but also decrease the consumption of resources. On the other hand, resource efficiency focuses on maximizing the use of raw materials, energy, and solvents throughout the production process.[31] Eco-friendly materials, known for their sustainability, biodegradability, or recyclability, play a crucial role in minimizing environmental impacts over their lifecycle. The reuse of these materials significantly diminishes the industry's reliance on virgin resources. Research by Rosen et al.[32] underscores the practicality and advantages of such resource-efficient practices within the coating manufacturing realm. VTT technical research in Finland[33] experts focus on transforming raw materials into sustainable ones inspired by nature, generating high-value products with minimal waste and new business opportunities. Additionally, strategies like Design for Disassembly (DfD) and Design for Adaptability (DfA) are vital, supporting the CE by facilitating the recycling and adaptation of products at the end of their primary use.[32]

Extended Producer Responsibility (EPR) schemes are also critical in this framework, ensuring that manufacturers take responsibility for their products throughout their lifecycle.[34] This responsibility encourages the design of sustainable and easily disposable products. By adopting circular design principles, products are engineered to maximize durability, longevity, and recyclability, aligning with eco-design concepts. Spreafico et al.[35] highlight the potential of eco-design strategies to minimize resource consumption throughout the product lifecycle. Moreover, the transition to circularity is supported by broader policy initiatives like the European Green Deal[36] and the CE Action Plan[37], which stress the importance of detaching economic growth from resource consumption and waste generation. The use of recycled materials can lead to cost savings, and the innovation driven by circular strategies can open new markets and bolster the industry's resilience in a resource-limited environment. These economic benefits are well-documented by the Ellen MacArthur Foundation[23], which reinforces the business case for circular economy practices.

A theoretical framework of industrial adaptation of CE has been sketched in Figure 3. CE strategies adopted by manufacturers vary in their names and the scale of adoption. Their adoption ranges from individual companies implementing isolated initiatives to entire industries embracing comprehensive circularity principles. The triple bottom line (TBL) serves as a sustainability framework to assess the success of these strategies, measuring their impact across three key dimensions: profit, people, and the planet.

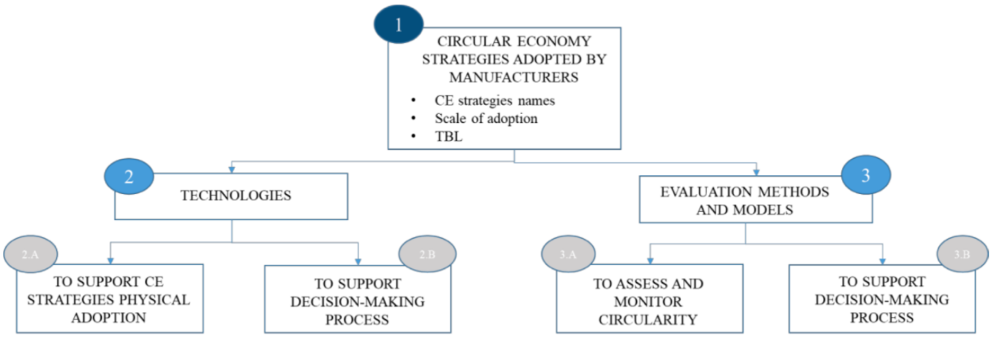

Figure 3. Theoretical framework of CE strategy adopted by industries.[38]

Technology plays a dual role in facilitating the practical implementation of a CE strategy and guiding decision-making processes within industries. Conversely, evaluation methods and models serve to gauge both the circularity and the feasibility of adopting processes that can be integrated into manufacturing companies.[38]

Consequently, there is an urgent need to promote the wider acceptance of sustainable practices across the ECI. Implementing a sustainable business strategy that emphasizes circularity involves using eco-materials for coatings, which are sustainably sourced, biodegradable, recyclable, or derived from renewable resources. Concurrently, adopting eco-processes helps minimize energy consumption, waste generation, and emissions while improving resource efficiency and environmental performance throughout the lifecycle of coating materials.[39]

2.3 Current EU regulatory and legislative framework aligned with coating industry

The European Commission's ground-breaking communication introduced a comprehensive CE package aiming to boost sustainable growth, job creation, and resource efficiency within the EU.[40] The package outlined strategies encompassing design for circularity, waste reduction, and recycling targets, demonstrating the EU's commitment to driving CE transformation. The current EU regulatory and legislative framework is closely aligned with the coating industry, emphasizing sustainable practices and pollution control.

The European Environmental Agency (EEA)[41] has reported the EU's CE initiatives highlighted the importance of holistic policy frameworks that address product lifecycles, consumption patterns, and material flows. Ghisellini *et al.*[42] and co-workers have emphasised a range of policies, including extended producer responsibility (EPR), eco-labelling, and eco-design regulations to drive circularity and reduce waste. The European Parliament's Resolution[43] emphasised the importance of circularity in achieving climate and environmental objectives. It called for measures to promote sustainable production, repair or reuse ability, and consumer awareness. The EU Zero Pollution Action Plan (ZPAP) introduced a "zero pollution vision for 2050," aiming to lower air, water, and soil pollution to levels deemed non-hazardous to health and the environment, thus fostering a toxic-free setting. The ZPAP explicitly mentions the term ‘circular’ in the context of the EU’s zero pollution ambition being complementary to the CE.[44] By adhering to the ZPAP objectives, the coating industry can contribute to creating a toxic-free environment and safeguarding human health and ecosystems from harmful pollution effects. Directive 96/61/EC[45] on Integrated Pollution Prevention and Control addresses reduction of emissions specially VOC and S(Semi)-VOC into all media from a large number of industrial sectors. Furthermore, to ban PFAS based coating, EU has taken steps such as restricting PFOS (PerFluoro-Octane-Sulfonic acid) and PFOA (Per-Fluoro-Octanoic-Acid) and signing international conventions to control these substances the EU under REACH Annex XVII (entry 53).[46]

The CE initiative advocates for a thorough and transformative approach to innovation, aligning its goals and actions with those outlined in Horizon 2020[47] and the Eco-Innovation Action Plan.[48] This alignment provides significant opportunities for fostering positive synergies and revitalizing business models. The integration of CE initiatives with existing innovation frameworks enables the application of valuable insights and available tools to drive change and innovation focused on extending product lifecycles. Protracting the lifespan of products holds substantial potential for reducing material consumption, energy usage, and waste generation.[49]

However, the lack of implementation of localised regulations hampers the successful transition to a CE. Many regulations are at the national level, resulting in variability and, in some cases, contradictions. Local governments often fail to strictly enforce regulations, leading to disparities in the usage of natural raw materials and creating challenges for companies striving to comply with multiple and sometimes conflicting regulations. Managing these complexities requires striking a delicate balance between policies promoting rapid innovation, leading to the introduction of superior and more resource-efficient products, and initiatives aimed at optimizing the long-term value of existing product stocks in both natural resources and economic terms.[50]

2.4 Circularity-related challenges specific to the coating industry

The transition from a linear to a CE in the coating industry faces obstacles in establishing closed-loop systems and fostering collaboration across the supply chain.[51] Below few challenges are elaborated on basis of new regulations and coating trends.

The formulation of coatings involves intricate chemical compositions, presenting a significant challenge to their effective recycling or reuse. Disassembling and separating various components prove costly and energy-intensive, hindering sustainable practices in the coating industry. Additionally, coatings often contain hazardous materials, such as VOCs, heavy metals, PFAS containing materials, making their safe management and disposal crucial to prevent environmental harm. VOCs, with a boiling point below 250°C serve as solvents in paints, ensuring stability, spread ability, and substrate delivery. The evaporation during and after application, VOC emissions can lead to irritation, headaches, and coordination issues. Severe reactions, including harm to the liver, kidneys, and central nervous system, as well as potential carcinogenicity, can occur due to the diverse compound range. Addressing these concerns necessitates innovative solutions and environmentally responsible practices within the industry.[52]

A notable challenge in lifecycle analysis (LCA) within the coating industry lies in accurately assessing the environmental impact at various stages of the product lifecycle.[53] While LCA aims to provide a comprehensive evaluation, not all companies have performed LCA of their products. LCA evaluates environmental impacts of a product, process, or service throughout its entire life cycle. It considers all stages, from raw material extraction to production, use, and end-of-life disposal. LCA aims to quantify the environmental burdens associated with each stage, including energy use, emissions, and resource depletion. By providing a comprehensive assessment, LCA enables informed decision-making to minimize environmental impacts and improve sustainability.[54] It aids the coating industry by identifying sustainability improvements, optimizing resource use, and reducing emissions. LCA supports CE principles[55], but challenges include data availability, methodological consistency and continuous development of new methods which demands redesign LCA of existing once.[56] From raw material extraction to production, application, and eventual disposal or recycling, complexities arise due to diverse formulations and applications. Variability in coating formulations, manufacturing processes, and usage patterns makes it challenging to generalize environmental impacts. Additionally, gathering comprehensive data throughout the entire lifecycle poses logistical challenges. Despite these complexities, a robust LCA is essential for identifying opportunities to enhance sustainability and circularity in coating processes and materials. Efforts to streamline data collection and refine methodologies are imperative to overcome these challenges and advance towards a more sustainable coating industry.[57]

Furthermore, the long lifecycles of coated products create a dual challenge. While longevity is advantageous, it requires ensuring the sustained effectiveness and sustainability of coatings throughout a product's life.[58] Meeting stringent quality and performance standards poses another hurdle, as the coating industry must balance adherence to industrial assurance systems with the adoption of more sustainable practices.[50],[59],[60] A lack of adequate infrastructure for recycling coatings further compounds the challenge, emphasising the need for cost-effective recycling methods and facilities tailored to the coating sector. Raising consumer awareness and ensuring economic viability, especially for smaller manufacturers, are essential aspects in driving the industry towards sustainability.[61–65]

3 RESEARCH METHODOLOGY AND APPROACH

This research focuses on developing a strategic framework to promote circularity within the ECI, driven by the imperative to address environmental challenges and champion sustainable practices. Employing a multidimensional approach, the study integrates a research roadmap based on literature reviews, case studies, books, scientific articles, web content, videos, and company's portfolio. The methodology aligns with university guidelines, ensuring proper data collection and analysis.

3.1 Research map

In this research, the analysis of Saunders Research Onion Model[66] (Figure 4) serves as a valuable tool, providing a step-by-step guide for crafting the research methodology. From the outer layer, which involves philosophical underpinnings and research philosophy, to the inner layers encompassing research approaches, strategies, methods, and data collection techniques, the model ensures a systematic and coherent development of the research design. This introduction sets the stage for a methodical exploration of each layer, offering clarity and structure to the process of constructing a robust methodology in line with the specific requirements of the research topics at hand.

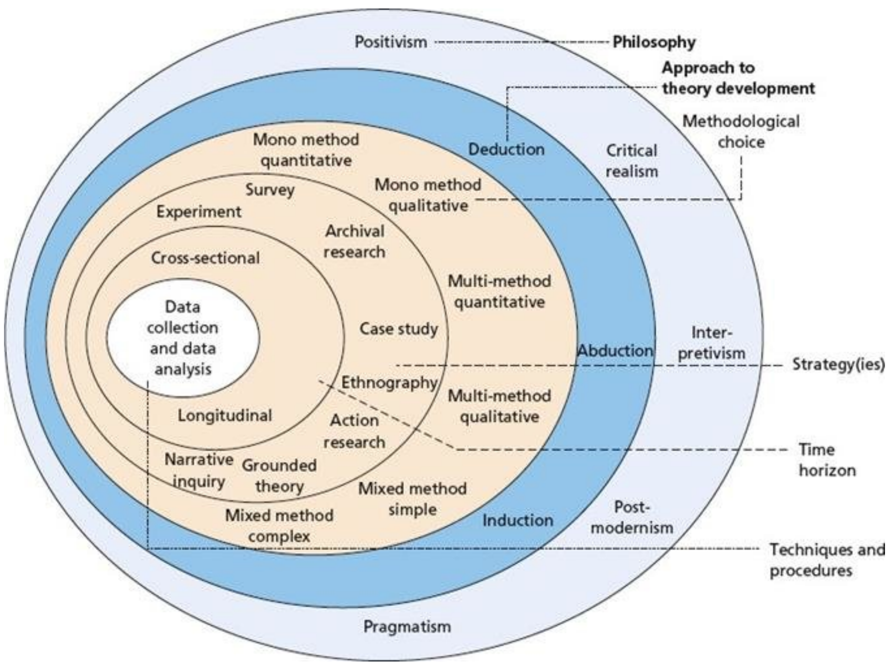

Figure 4: Research onion model: A comprehensive model for research design.[67]

To comprehensively understand how the typical coating industry is performing in implementing the CE in their business decisions, a combination of qualitative and quantitative methods have been employed. Qualitative methods, such as in-depth case studies have offered insights into the industry's decision-making processes. Additionally, quantitative data analysis of industry reports and performance metrics has provided a broader perspective on trends and patterns.

Investigating the current adherence of the coating industry to EU directives and regulations necessitates a thorough approach. It involves analyzing official directives and industry reports, supplemented by insights from regulatory experts and industry professionals.[5] This methodological combination ensures a comprehensive grasp of the industry's compliance landscape, elucidating both formal adherence and practical implementation challenges. Emphasis is placed on understanding the intricacies of materials like paints and coatings, their application methodologies, and the imperative for precision in their utilization. Moreover, it underscores the interconnectedness of regulations, industry practices, and stakeholder responsibilities in guaranteeing safety and regulatory compliance.[68]

Identifying possible shortcomings in implementing a sustainable and CE-oriented process in the coating industry involves a multi-faceted approach. A thorough literature review has provided the insights into existing challenges and potential solutions.[64] Content analysis of industry reports have complemented this by gathering real-world data on issues. This mixed-methods approach ensures underscores the need for developing coatings that are easier to separate and recycle, or that can degrade environmentally without harmful residues, thus aligning with the principles of sustainability and circular economy.

The research was qualitative while conducting the case studies on a company's culture, ethics, goals, and circular initiatives that allows for an in-depth exploration and understanding of the complex and contextual nature of organizational phenomena.[69] The assessment of company culture, ethics, and goals were achieved through company website and document analysis. The study of circular initiatives within the company can benefit from qualitative data collection methods, enables to delve into the motivations, challenges, and outcomes of such sustainability practices.

Moreover, the methodological connection establishes a systematic framework for investigating the industry's performance, compliance, shortcomings, and future strategies. By aligning methods with specific research questions, the study ensures that each aspect of the research problem is addressed comprehensively. The combination of qualitative and quantitative methods allows for a triangulation of data, enhancing the reliability and validity of the findings. This systematic approach not only ensures the rigor of the research but also facilitates the development of a coherent narrative that addresses each research question. In essence, the chosen methodology becomes the backbone of the research design, ensuring that the study is both comprehensive and methodologically sound in tackling the complexities of the coating industry's journey towards sustainability and CE implementation.

3.2 Data collection

In conducting a comprehensive study on the effectiveness of ECIs, a strategic approach was employed to gather data and insights from companies of varying sizes: large corporations, medium-sized enterprises, and start-ups. The companies were carefully chosen to represent different stages of growth and sectors within the industry to ensure a diverse range of ECIs. This selection aimed to illuminate how different organizational sizes and types implement circular economy principles and the varying impacts these implementations have on their sustainability goals. By including a wide spectrum of companies, the study could capture a broad perspective on the adaptation and effectiveness of circular economy practices across the business landscape.

The primary method for data collection involved a detailed examination of company websites. This allowed for an in-depth analysis of their mission statements, sustainability initiatives, and specific practices related to the circular economy. Additionally, the study included a thorough review of relevant literature, such as academic articles and open-access resources, which provided a theoretical framework and industry insights.

Main source for data collection for this research are:

- Andor (TAMK library access)

- Elsevier literature search
- Google scholar

Company brochures and press releases have also provided valuable documents for understanding official stances, recent innovations, and strategic directions of the firms. To gain a practical perspective, videos featuring industry leaders discussing their sustainability efforts have been also examined. Archival research has been conducted to analyse existing data such as analysing Key Performance Indicators (KPI) with a focus on understanding the historical context and trends towards circularity. The careful selection and utilisation of these instruments aim to triangulate information from various sources, ensuring a robust and multifaceted understanding of how the ECI, across its diverse spectrum, navigates the challenges and opportunities associated with implementing CE principles and adhering to EU directives.

In conducting case studies interviews or one-to-one discussions with company representatives were not feasible due to time constraints and confidentiality concerns. The focus of the study centred on analysing each company's sustainable and circular initiatives, with a particular emphasis on identifying loopholes, limitations, and challenges. The absence of direct interviews was compensated by a comprehensive examination of publicly available information, offering valuable insights into the unique approaches and challenges faced by companies of varying sizes within the ECI. The results of this research aim to contribute to a deeper understanding of sustainable practices in the coating sector and provide meaningful recommendations for industry stakeholders and policymakers.

3.3 Data analysis

Data analysis was conducted through a comprehensive, mixed-methods approach, which was tailored to effectively address each research objective and question.

For RQ1, qualitative and quantitative analyses were blended to evaluate the current state of sustainability and CE principal integration within the ECI. This involved published articles from industry experts, in-depth analysis of case studies of companies excelling in CE practices, and the analysing of survey data for trends. Quantitative data from surveys were statistically analysed to identify trends, while qualitative data from freely accessible online data provided deeper insights into the effectiveness and challenges associated with integrating CE principles.

In addressing RQ2, the environmental ramifications and challenges associated with both linear and circular production models were delved into. This was achieved by the examination of peer-reviewed literature, environmental reports, and sector-specific data from company website. Emissions, waste production, and resource utilization figures were quantitatively assessed, while insights into the regulatory and market barriers were provided through qualitative evaluations. The distinct environmental footprints of linear versus circular methods were pinpointed by LCAs conducted by industry professionals.

For RQ3, the focus was on the identification of actionable opportunities and proven strategies for CE adoption within the coating sector. A combination of qualitative and quantitative methods, including case studies and industry report analyses were used to pinpoint vital opportunities for advancing CE. These opportunities range from innovating waste management techniques, optimizing coating processes to lessen resource consumption and environmental impact, recommending bio-based materials to reduce dependency on non-renewable resources. Effective circularity and sustainability practices were pinpointed through the comparative analysis of companies' energy use, waste handling, the adoption of renewable resources and cutting-edge technologies.

Lastly, for RQ4, a detailed qualitative examination of case studies was involved to carve out actionable strategies for steering the coating industry towards greater sustainability and circularity. This analysis pinpointed existing shortcomings and potential areas for policy and strategic enhancement. Although direct interviews were not conducted, a solid groundwork for crafting meaningful policy and practical recommendations was laid by a rigorous review of available public resources. Recommendations were formulated with an eye towards maximizing environmental and economic gains, propelling the industry towards a more circular and sustainable future.

3.4 Limitations of research methodology

This study's methodology faces certain limitations that could affect the depth and scope of its conclusions. A significant challenge is the potential unavailability of proprietary or confidential data within the coatings industry, where trade secrets and specialized technologies prevail. Moreover, due to competitive pressures, companies might be hesitant to reveal detailed aspects of their operational strategies, leading to data that may be incomplete or biased. Constraints related to time and resources further restrict the ability to conduct thorough interviews and on-site verifications.

Relying exclusively on publicly available data and literature for this research introduces a risk of selection bias, as it confines the analysis to information that companies choose to make public. This approach may omit critical internal data or viewpoints from organizations that are less forthcoming, potentially skewing the insights into more private and innovative practices and affecting the findings applicability across different settings.

Despite these challenges, this study attempts to mitigate such issues by rigorously analyzing available information from diverse sources, thereby aiming to enhance the validity of the research and provide meaningful contributions toward the study goals. Employing a transparent and systematic methodology ensures the robustness and reliability of the findings, helping to equip researchers and industry stakeholders with the knowledge to adopt sustainable practices that align with CE principles as they are directly responsible for adopting these practices in real-world settings.

4 CASE STUDIES: APPROACH TOWARDS CIRCULARITY AND SUSTAINABILITY IN COATING INDUSTRY

As the global emphasis on sustainable practices intensifies, the coating industry is increasingly turning its focus toward CE initiatives. In the current landscape of evolving regulations and legislation, the coating industry recognises the imperative to align with CE principles, shedding light on how these practices not only address environmental concerns but also position companies in compliance with the dynamic regulatory frameworks governing sustainable practices. Embracing CE principles in the coating industry is not merely a choice but a strategic imperative for fostering environmental stewardship and ensuring long-term resilience in a rapidly evolving regulatory landscape.

In this chapter, four representatives from the ECI 1) BASF, 2) Covestro, 3) Hempel, and 4) Brightplus Oy were selected, covering a range from large to small enterprises across Europe. The portfolios of the companies are listed in Table 1. Through the examination of these varied industry participants, comprehensive insights into the current landscape were obtained, enabling the development of targeted strategies to improve the overall sustainability and effectiveness of the ECI. This strategic selection was made to explore the unique initiatives undertaken by each company, identify existing gaps, and highlight areas for collective enhancement.

Table 1: Company's portfolio of BASF, Covestro, Hempel & Brightplus Oy

Company	**BASF**[70]	**Covestro**[71]	**Hempel group**[72]	**Brightplus Oy**[73]
Location	Ludwigshafen, Germany	Leverkusen, Germany	Lyngby, Denmark	Oulu, Finland
Founded (year)	1865	1863 (Bayer) 2015 (Covestro)	1915	2014
Business	Chemicals, materials, industrial solutions, surface technologies, nutrition & care and agricultural solutions	Coating and adhesives. Also, business in isocyanates and polyols for cellular foams, thermoplastic polyurethane and polycarbonate pellets, as well as polyurethane-based additives	Global supplier of coatings and paints in the protective, marine, decorative, container and yacht industries.	Coating and Materials. Sustainable solutions for coatings and biomaterials
Employee	111,481 (2022)	17985 (2022)	7500 (2022)	20-50 (2022)

4.1 CE initiatives by BASF

BASF, with a history spanning over 150 years, remains steadfast in its commitment to CE principles. At the heart of its strategic efforts, the company is focusing on promoting CE through three main areas: 1) Utilization of new feedstock, including alternative raw materials; 2) Establishment of innovative material cycles; and 3) Development of novel business models embracing digital and service-oriented concepts (see Figure 5).

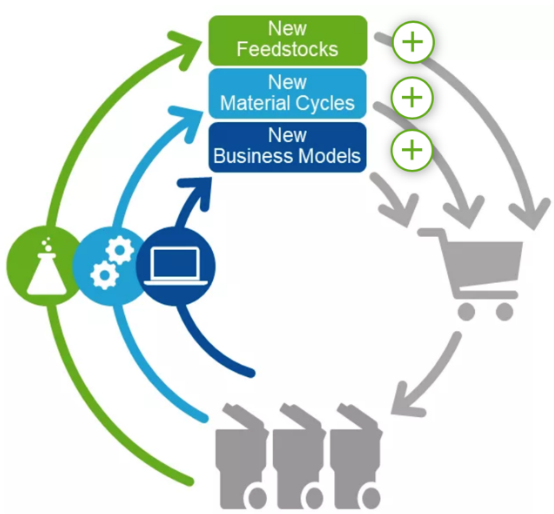

Figure 5: BASF CE principle by increasing new renewable feedstock, shaping new material cycles and creating new business models.[74]

Regarding new feedstock, BASF has been proactively shifting away from fossil fuel-based sources to recycled and renewable alternatives. With a substantial network comprising over 6,500 suppliers who adhere to rigorous environmental and social criteria, BASF sources approximately 35,000 distinct raw materials. Noteworthy instances include bio-based feedstock like 2-Octyl acrylate, utilized across various applications such as adhesive formulation and coating applications. This holistic approach not only diminishes carbon emissions but also improves product efficacy.[75],[76]

4.1.1 Steps taken to implement CE strategies

In order to avoid the dependency of natural resources which impacts on several environmental issues, BASF has encapsulated '3R' principles meaning, reduce, reuse, and recycle. One approach is to incorporate bio-based and renewable raw materials in the production processes, demonstrating an initial commitment to sustainability. BASF has pioneered innovative approaches such as the biomass balance method.[77] This innovative process entails the transformation of organic waste or vegetable oils into bio-naphtha or bio-gas, which is then seamlessly integrated into the production Verbund[78] system. This system aims to minimize raw material and energy consumption, resulting in cost savings within the interconnected production process.

Additionally, BASF employs the mass balance approach[79], systematically tracking materials throughout the production process. By incorporating renewable or recycled feedstock alongside traditional sources, this method facilitates a faster transition to a carbon-neutral circular economy without compromising product quality or affordability. This approach is particularly advantageous for industries reliant on a limited range of raw materials, enabling seamless integration of sustainable practices without significant infrastructure investments.

Innovating within the realm of business models, BASF introduces solutions like Infrared Spectroscopy (trinamix)[80], a user-friendly mobile spectrometer ideal for chemical analysis in recycling facilities and industries embracing CE principles. This plug-and-play solution underscores BASF's commitment to facilitating faster, easier, and more flexible adoption of CE practices across diverse sectors.

4.1.2 Environmental impacts

To reduce finite resource and carbon footprints associated with products and solutions, BASF is using recycled and renewable raw materials with the existing raw material base. BASF has identified five levers to reduce greenhouse gas emissions: 1. Grey-to-green: meaning the electricity produced from renewable sources 2. The implementation of Power-to-Steam technology, replacing gas-powered furnaces with electrically heated steam cracker furnaces, has resulted in a significant reduction of nearly 90% in CO_2 emissions,[81] 3. New technologies, 4. Bio-based feedstocks, 5. Continuous operational excellence activities (opex).[82] BASF's climate goal is to achieve net zero CO_2 emissions by 2050.[83] In Figure *6*, the greenhouse gases emissions e.g., methane (CH_4), CO_2, nitrous oxide (N_2O), hydrofluorocarbons (HFC) over 5 years were shown.[84] Among gases, nitrous oxide (N_2O) release has dropped significantly over years. BASF is targeted to reduce 40% CO_2 (15,000 metric tons) reduction by using renewable raw materials for vehicle coatings by 2030.[85]

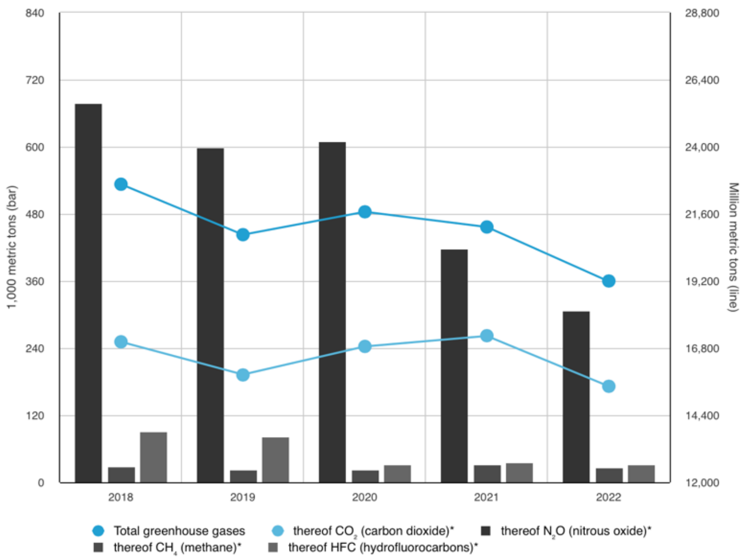

Figure 6: Development of BASF group's greenhouse gas emissions (from 2018-2022).[84]

4.1.3 A case study of material and process innovation

Introduction The automotive coating processes pose a notable environmental challenge compared to other stages of vehicle manufacturing. Traditionally viewed as solely aesthetic, these processes are both energy-intensive and substantial contributors to VOCs and CO_2 emissions, which worsen air pollution and contribute to global warming.[54] BASF has embarked on a mission to address these challenges by introducing CathoGuard® 800[86],a ground-breaking leap in sustainable innovation within automotive coating while maintaining economic effectiveness and ecological efficiency.[87]

Challenge Balancing economic and ecological considerations in automotive coating poses a daunting challenge. The conventional car coating, which is 0.1 mm thick, comprises four layers, caused significant consumption of materials, space and energy. Furthermore, the requirement for primer, a preparatory coating applied to materials to shield the electrodeposition coat (e-coat) from Ultra-violet (UV) light and stone chipping, adds complexity to the efforts aimed at streamlining the process.[88] BASF recognized the need for a solution that could reduce energy consumption, VOC emissions, and renewable raw material usage without compromising on quality or protection.[89]

Solution BASF's innovative approach, embodied in the “Integrated Process II”, a novel highly efficient coating technology reimagines the traditional coating process.[90] By optimizing the coating sequence and incorporating part of the primer's functions into the waterborne in the base layer system[91], BASF streamlined the process from four steps to three. The groundbreaking innovation, CathoGuard® 800 (CG800)[92] advanced e-coat technology by eliminating the primer layer while preserving the protective characteristics of conventional process. It explores environmentally friendly automotive coatings, coating methods, and solutions, aiding car manufacturers in addressing the pressing challenges of balancing economic viability with ecological sustainability.

Results The implementation of BASF's streamlined “Integrated Process II”, particularly at the Tiexi plant of BMW Brilliance, has yielded around a 30% decrease in both initial investment and labour expenses, underscoring its economic benefits.[93] In contrast to the conventional method, the “Integrated Process II” significantly abbreviates the production line and coating process.[94] The decrease in raw material usage reduces 20% less CO_2 emissions, therefore, releasing low VOC that showcased significant progress in sustainable development.

Furthermore, it assists car manufacturers in enhancing productivity and achieving a better equilibrium between energy usage and ecosystem preservation. BASF's involvement, from construction to start-up, ensured the successful implementation of the IP and the continuous stable production of the paint shop.[94]

Sustainability and circularity BASF's CathoGuard® 800 plays a pivotal role in driving sustainability and circularity in automotive coating. CG800 is considered an eco-friendly e-coat due to rust-resistant, low in solvent, and free of heavy metals, hazardous air pollutants (HAPs) process. It optimized film distribution ensures material savings while maintaining high quality. The multi-metal compatibility of CG800 reduces the need for multi-process, further minimizing material consumption. By eliminating the primer step and maximizing the utilization of CG800, BASF not only reduces resource consumption and emissions but also enhances the efficiency, productivity and innovation process.[95]

4.1.4 Key performance indicators (KPIs)

Key performance indicators (KPIs) serve as vital metrics that organisations use to evaluate and measure their progress toward strategic goals and objectives. BASF has set itself ambitious targets along the value chain. In Table *2*, only the KPI related to environmental and sustainable issues are given.[96]

BASF emphasizes innovation as fundamental to its success, leveraging the expertise of its 10,000 global research and development employees. With €2,298 million invested in R&D in 2022, 83% focused on divisional application-specific projects. Prioritizing sustainability, BASF develops products aiding customers' environmental goals, contributing to a €12 billion revenue from new product sales since 2017. The reorganization in 2022 aligns research closely with customer needs, reducing time to market. Group Research addresses cross-divisional sustainability challenges, while corporate funding fosters broader research initiatives. BASF intensifies efforts in Asia, exemplified by the expanded Shanghai Innovation Campus. Strong patent filings underscore BASF's innovative prowess, with a focus on sustainability innovations.[97]

Table 2: Key performance indicators (KPI): BASF's goal, target, and achievement in 2022

KPI	Goal	Target	Achievement
Reduce CO_2 emissions	Reduction of CO_2 emission is set to 25% by 2030 (baseline: 2018)	2030 target is 16.4%	Status in 2022 is 18.4% which is already very close to target
Improve sustainability evaluations	Spend 90% in sustainability evaluations by 2025	2025 target is 90%	Status in 2022 is 85%
Improve sustainability in the supply chain	Sustainability performance of 80% suppliers needs to be improved upon re-evaluation	2025 target is 80%	Status in 2022 is 76%
Advanced sustainable water management	Implement sustainable water management at BASF production sites and at BASF Verbund sites by 2030	2030 target is 100%	Status in 2022 is 61.6% which needs to be improved within short period

4.2 CE initiatives by Covestro

Covestro is committed to preserving the essential elements of life and aims to create lasting value in line with its sustainability principles encapsulated in the "People, Planet, Profit" ethos. Innovation and sustainability are the driving forces behind the continuous improvement of Covestro's products, processes, and facilities. This progress is facilitated through the utilization of alternative raw materials, renewable energy sources, innovative recycling methods, collaborative solutions, and CQ solution[98] stands for 'Circular Intelligence', a smarter approach to more sustainable materials and technologies incorporate at least 25% alternative, non-fossil raw materials. Covestro's vision is to actively pursue the CE, a significant societal and economic initiative aimed at achieving global climate neutrality and conserving dwindling resources as shown in Figure 7.

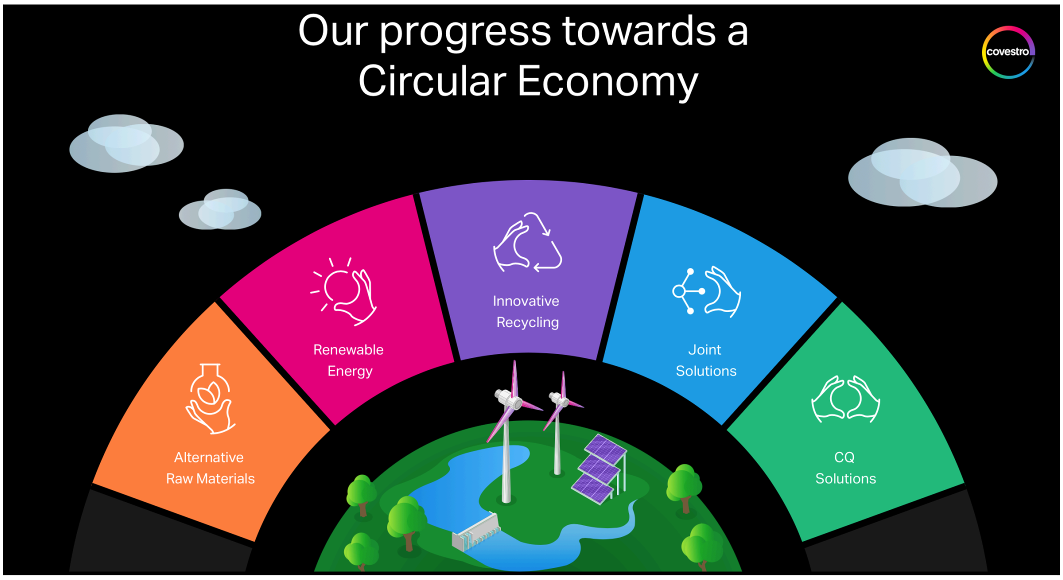

Figure 7: Progress towards circular solutions of Covestro to cover three relevant core business, coatings, adhesives and specialties[99]

4.2.1 Steps taken to implement CE strategies

Covestro actively collaborates across the value chain to advance CE principles, engaging with partners to exchange knowledge and resources, fostering a collective commitment to sustainability.[100] Taking steps toward climate neutrality, the company has signed multi-year power purchase agreements with China General Nuclear Power (CGNP), integrating solar and wind power to reduce its carbon footprint and contribute to the global shift towards clean energy.[101] In the realm of innovative recycling, Covestro leads the "CIRCULAR FOAM" project, aiming to save one million tonnes of waste and 2.9 million tonnes of CO_2 by 2040.[102,103] Chemical upcycling of waste streams creates virgin-equivalent feedstock for high-performance plastics, making strides towards climate neutrality. Exploring alternative raw materials, Covestro focuses on bio-based solutions like Hexamethylenediamine (HMDA) for nylon-6,6, an important raw material for coatings and adhesives, reducing reliance on traditional fossil fuels.[104]

Covestro is actively advancing circularity within its supply chain by implementing sustainable practices. The company focuses on sustainable sourcing, optimising transportation efficiency, and fostering engagement with suppliers. Recognising the critical role of supply chain sustainability in value creation and risk reduction, the company assesses economic, social, ethical, and environmental standards for its suppliers, with 61% showing improved sustainability performance in fiscal 2022.[105]

4.2.2 Environmental impacts

Covestro measures greenhouse gas (GHG) emissions in accordance with GHG Protocol standards[106] across its two production lines. Scope 1 covers direct emissions such as those from fossil fuel combustion and production processes, including CO_2, nitrous oxide (N_2O), methane (CH_4), fluorinated hydrocarbons, and sulfur hexafluoride (SF_6). Scope 2 entails indirect emissions from external energy sources used at environmentally impactful sites. Covestro predominantly uses the market-based method to calculate Scope 2 emissions. Scope 3 encompasses all other emissions within the value chain. In one-year Covestro has observed a 9.2% reduction in absolute Scope 1 and Scope 2 GHG emissions, with direct emissions rising by 1.3% and indirect emissions declining by 11.8% (Figure 8). These changes were primarily driven by reduced production activity, lower energy demand, alterations in local emission factors, and increased reliance on renewable energy sources like at the Shanghai site, where over 30% of electricity demand was met through renewables, consequently reducing Scope 2 emissions. Overall, these initiatives contributed to a decrease in calculated GHG volumes.[107]

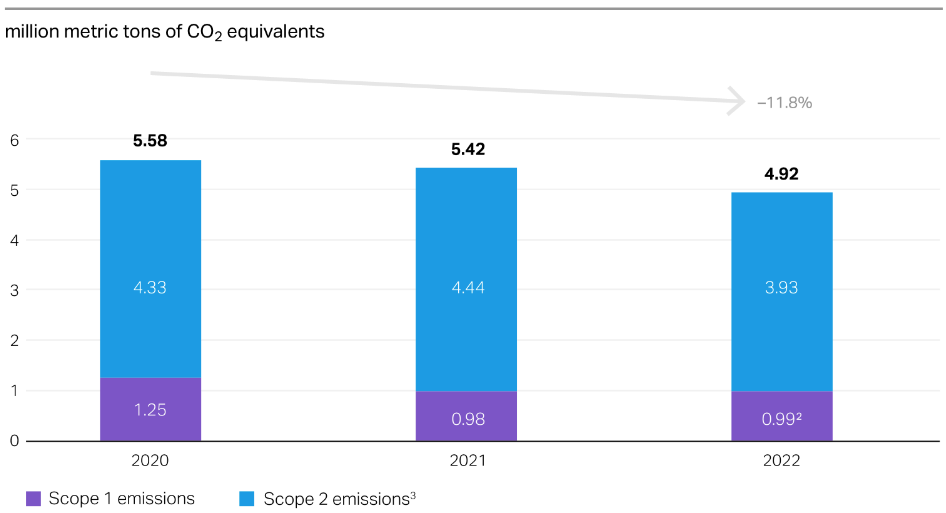

Figure 8: Scope 1 (direct) and scope 2 (indirect) GHG emission,[107]

4.2.3 A case study of technological innovations

Introduction Exploring Covestro's Powder Coating Resins: A Comparative Analysis of Carbon Footprints[108] explored how Covestro's powder coating resins represented a green and sustainable solution within the realm of coating technologies. This technology operated without solvents, resulting in a minimal release of VOCs. The transition from solvent-based coatings to powder coatings or waterborne paints was shown to have great potential in mitigating CO_2 emissions. This case study scrutinized the carbon footprints associated with different coating systems, underlining the beneficial environmental impact of powder coatings.[108]

Challenges Solvent-borne coatings exhibited higher carbon footprints due to increased paint usage, energy consumption for solvent evaporation, and air heating compared to powder coatings. The study aimed to quantify these differences and identify opportunities for emissions reduction.

Solution Using the LCA methodology, this study assessed the carbon footprint associated with the manufacturing processes of resin and coatings, as well as their application onto metal substrates. Covestro employed SimaPro LCA software and the ecoinvent database[109] to gather environmental impact data, IPCC GWP 2013[110] for carbon footprint calculations, ReCiPe 2008[111] for assessing environmental impact, and internal LCA expertise to execute the analysis. Notably, the analysis excluded CO_2 emissions from paint disposal at the end of the coated object's service life. Eleven coating formulations, encompassing powder coatings, waterborne paints, and solvent-borne coatings, underwent examination.[108] As shown in (Figure 9) coating includes 1) powder coatings for interior and exterior use (70/30Hybrid, 93/7TGIC, 95/5HAA, 95/5HAA EasyCure, 70/30 Hybrid HT 40µ) 2) waterborne industrial alkyd coating (watersolvable (WS Alkyd), 3) solvent-borne polyester and acrylic based coatings (Saturated(SA)Polyester(PE)conventional, Acrylicconventional, Acrylic high solid, Saturated polyester high solid).

Results Powder coatings demonstrated the lowest carbon footprint, particularly when applied in thinner layers, emitting approximately 0.3 kg CO_2 eq per m^2. Waterborne paints and thicker powder coatings exhibited slightly higher emissions, ranging from 0.3 to 0.4 kg CO_2 eq per m^2. Solvent-borne and high solids coatings generated the highest emissions, ranging from 0.44 to 0.6 kg CO_2 eq per m^2.

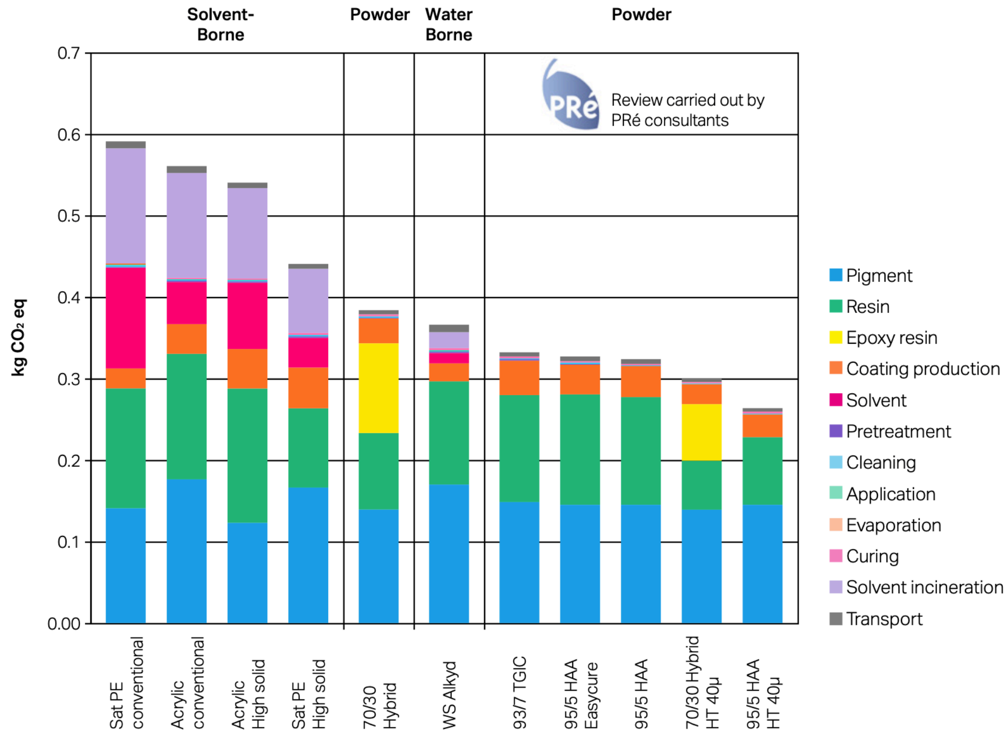

Figure 9: LCA studies of 13 industrial coating formulations applied to 1 m^2 of steel substrate.

Transitioning to powder coatings presents a significant opportunity for reducing CO_2 emissions in coating applications. Strategies such as optimising layer thickness, exploring epoxy/hybrid replacements, and adjusting curing parameters can further enhance the environmental performance of powder coatings.[112] Sustainable coatings play a crucial role in mitigating carbon footprints across the value chain, emphasising the importance of eco-friendly coating solutions in industrial practices.

4.2.4 Key performance indicators (KPIs)

Key performance indicators (KPIs) for measuring carbon neutrality are pivotal in Covestro's sustainability strategy. Table 3 illustrates the company's net-zero greenhouse gas emission goal and the progress made towards achieving it. Covestro's 2020 objective was to achieve net-zero Scope 1 and Scope 2 emissions by 2035, aiming to slash emissions by up to 98.2% compared to 2020 levels (96.52%). By 2030, they plan to reduce direct and indirect GHG emissions to 2.2

million metric tons from the 5.6 million metric tons of CO_2 equivalents recorded in 2020. Although residual emissions of 0.1 to 0.2 million metric tons could persist by 2035, there was an 8.4% reduction in GHG emissions by 2023. Additionally, Covestro targets net-zero Scope 3 emissions by 2050, intending a 30% reduction by 2035. Scope 3 emissions, lower by 7.0% in 2023, represented 75.5% (77.5% in previous year) of the Group's total GHG emissions.[113] Covestro foresees coatings and adhesives playing a pivotal role in extending product lifetimes, reducing environmental impact, and partnering across the value chain to drive sustainable solutions.[114]

Table 3: Covestro – Annual report 2023 emphasizing greenhouse gas emission.[113]

GHG emissions (million metric tons of CO_2equivalents)[1]

	2020	2021	2022	2023
Scope 1 GHG emissions				
Gross Scope 1 GHG emissions	1,25	0,98	0,99	0.93[2]
Scope 2 GHG emissions[3]				
Gross location-based Scope 2 GHG emissions	4,48	4,40	3,82	4,10
Gross market-based Scope 2 GHG emissions	4,33	4,44	3,93	4,18
Significant Scope 3 GHG emissions[3, 4]				
Gross Scope 3 GHG emissions		21,84	16,95	15,75
1 Purchased goods and services		16,44	12,43	11,86
2 Capital goods		0,34	0,45	0,52
3 Fuel and energy-related Activities		1,02	0,83	0,81
4 Upstream transportation and distribution		0,49	0,53	0,52
5 Waste generated in operations		0,16	0,13	0,10
12 End-of-life treatment of sold products		3,34	2,53	1,89
Other categories		0,05	0,05	0,05
Total Gross GHG emissions				
Total location-based GHG emissions		27,22	21,76	20,78
Total market-based GHG emissions		27,26	21,87	20,86
Total Net GHG emissions				
Sold compensation actions		0,63	0,57	0.65[5]
Total market-based GHG emissions including compensation actions		**27,89**	**22,44**	**21,51**

([1]Scope 1, Scope 2, and Scope 3 GHG emissions determined as set out in the financial control approach of the GHG Protocol; global warming potential (GWP) factors according to the IPCC's Sixth Assessment Report.[2] In the year 2023, 81.8% of emissions were CO_2 emissions, 17.7% were N_2O emissions, 0.3% consisted of partly fluorinated hydrocarbons, and 0.1% each were attributable to CH_4 and SF_6.[3] In combustion processes, only CO_2 was calculated as indirect emissions.[4] Data collected since fiscal year 2021)

4.3 CE initiatives by Hempel

Hempel has embarked on various CE initiatives to promote sustainability. In 2022, the company introduced a comprehensive circularity roadmap aimed at reducing waste and enhancing environmental stewardship. One of their ambitious goals is to significantly reduce customer waste through innovative practices. Additionally, by 2025, Hempel aims to achieve a substantial milestone of incorporating 50% recycled content in its primary plastic packaging, demonstrating a commitment to circularity and resource conservation.

4.3.1 Steps taken to implement CE strategies

Hempel has introduced ‘Futureproof’ a framework through which the company can deliver on CE strategic goal to turn ambitions into actions.[115] Futureproofing entails translating ambition into tangible actions, necessitating the integration of sustainability across all facets of business operations. The framework comprises four key divisions: Performance, Products, Partners, and People.

Under Performance, goals include achieving carbon neutrality in internal operations by 2025, phasing out hazardous materials, and minimising waste generation. Product initiatives prioritise sustainability in development, aiming to reduce CO_2 emissions and waste while enhancing circularity. Partnerships emphasise collaboration to reduce CO_2 emissions throughout the value chain and promote ethical practices. People-centric goals focus on safety, health, diversity, and inclusion, striving for gender balance and fair compensation while offering flexible benefits and family support program, thus fostering a holistic approach to sustainability and corporate responsibility.[116]

4.3.2 Environmental impacts

Hempel's attainment of a B rating from CDP[117], a non-for-profit charity who runs the global disclosure systems, underscores its dedication to environmental transparency and management. By participating in CDP's disclosure process, Hempel addresses increasing calls for environmental responsibility. With science-based targets validated, Hempel pledges to slash its carbon emissions from internal operations by 90% by 2026, aligning with efforts to limit global warming to 1.5°C. Beyond addressing Scope 1 and 2 emissions, Hempel ambitiously aims to halve its Scope 3 emissions across its entire value chain by 2030.[118]

4.3.3 A case study of technological innovations

Introduction Antifouling coatings were crucial for enhancing efficiency both in drydock and at sea. Without such coatings, marine vessels experienced fouling, characterized by the accumulation of organisms like algae and barnacles on hull surfaces. This fouling significantly increased drag, lowered speed, and escalated fuel consumption, thereby increasing operational expenses. Moreover, it posed risks such as corrosion, shortening the lifespan of vessels, and facilitating the spread of invasive species, thereby contributing to ecological imbalances.[119]

Challenge During the new build outfitting period, vessel owners and shipyards faced the shared challenge of controlling fouling buildup, which had become increasingly crucial. Vessels like bulkers, container ships, and oil tanker carriers could idle for up to four months, while very large cruise carriers (VLCC), cargo only tanks (COT), liquefied natural gas carriers (LNGC), and drill ships might sit idle for even longer, battling fouling on hull coatings.[120] Climate change exacerbated the issue, with warming waters promoting fouling growth, necessitating high-performance biocides. Delivering fuel-efficient vessels in optimal condition without requiring additional restorative work became a collective priority, underscoring the necessity for antifouling coatings to perform exceptionally under these evolving conditions. Furthermore, the challenge was to explore eco-friendly antifouling methods due to stricter global environmental regulations. Innovations in marine chemistry, surface design, and biofouling understanding were critical for sustainable marine solutions.[121]

Solution Hempel's Hempaguard®[122] offered three-coat and five-coat system where Hempaguard Max was three-coat for operational flexibility and fuel efficiency, while Hempaguard® X7[123] utilised five coats for warm waters. Both innovations featured low Average Hull Roughness (AHR) for reduced drag and enhanced out-of-dock fuel savings. Actiguard® technology[124] with enhanced hydrogel ensured superior smoothness and antifouling performance. The hull performance, defined as hull moved through water, which directly influenced fuel consumption, speed, and overall vessel stability, Hempel's innovations, Hempaguard X7 and Hempaguard Max, was evaluated over time. Hempaguard Max demonstrates performance closely aligned with ideal hull performance, indicating its effectiveness as shown in Figure 10.

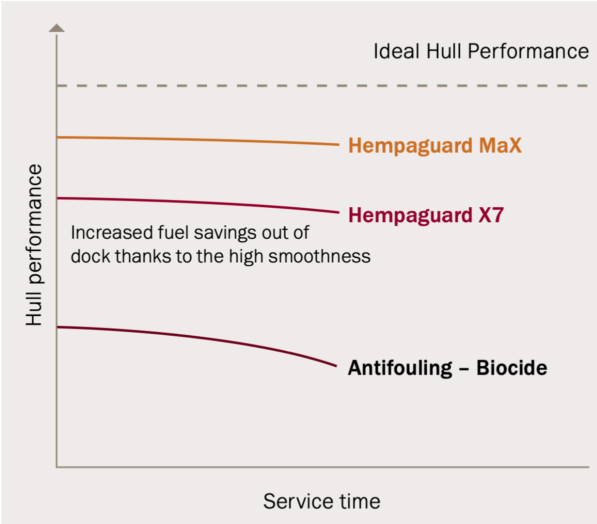

Figure 10: High performance hull coating compare to other coating .[125]

Results Since its introduction in 2013, Hempaguard had been applied to over 3,000 ships, leading to a significant reduction of 27 million tons of CO_2 and saving 8.6 million tons of fuel, thanks to smoother hulls. Actiguard® technology, applied in either a three-coat or five-coat system, achieved exceptional antifouling efficiency. Over a period of five years, the speed loss was just 1.2% for Hemmpaguard X8 and 1.4% for Hempaguaard X7, compared to the market average for conventional antifouling coatings.[126] This performance was measured using the ISO 19030 methodology.[127] Hempaguard notably reduced fuel consumption with an average of 6%, docking expenses, and off-hire periods, while significantly improving fuel efficiency post-docking. Hempaguard X7 was recognized as the industry's most robust fouling defence, aiming to cut down on fuel and maintenance costs.[128]

4.3.4 Key performance indicators (KPIs)

Hempel's key performance indicators (KPIs) are centered around sustainability goals. These include reducing scope 1 and 2 CO_2 emissions by 90% by 2026 from the base year 2019, screening 70% of direct and indirect spend suppliers by 2025 for sustainability, achieving zero waste to landfill from production sites by the end of 2025, and reducing hazardous (red) raw materials by 25% by the end of 2025. These targets are in alignment with the Science Based Targets initiatives (SBTi), a corporate climate action organization, for 1.5°-degree campaign and demonstrate Hempel's commitment to reducing its environmental impact.[129] Hempel has integrated sustainability into its financing, with interest margin adjustments based on its ability to meet these ambitious sustainability goals, signalling a comprehensive approach to environmental responsibility across its operations and value chain.[130]

Hempel's commitment to sustainability extends to including Carbon Footprint Data (CFD) on over 160 products, with plans to cover all solutions in Marine, Energy, and Infrastructure industries by Q1 2024. These initiatives leading to the integration of carbon footprint information directly onto Product Data Sheets and empower customers to make informed decisions aligned with their sustainability commitments. The Scorecards encompass key metrics covering environment, circularity, and chemicals, facilitating quick evaluation of the environmental impact of various paint systems.[131]

4.4 CE initiatives by Brightplus

Despite being a relatively new entrant, Brightplus has proactively engaged in numerous collaborative projects with research institutions and industry partners. Their focus is on innovating biobased, lightweight, and recyclable applications geared towards luxury coatings, bioplastics, and new material development. Demonstrating a commitment to environmental responsibility, Brightplus meticulously conducts sustainability assessments across its research, development, and manufacturing processes. The company has gone a step further by achieving ISO14001:2015 certification[132], underscoring its dedication to maintaining a robust environmental management system. This certification not only validates Brightplus's commitment but also provides a structured framework for the organisation to design, implement, and continually enhance its environmental performance, solidifying its stance in sustainable practices.

4.4.1 Steps taken to implement CE strategies

Brightplus actively implements CE strategies, prioritizing sustainability, and environmental responsibility. The company emphasizes the use of eco-friendly and renewable raw materials, showcasing a strong commitment to circular practices in their business operations. Environmental sustainability is central to Brightplus, offering solutions devoid of harmful chemicals, conflict minerals, and rare earth elements. An example is their BrightBio thermolusters[133], which are lead, cadmium, and uranium-free coatings applied on hot glass, although containing dichloromethane classified as harmful under dangerous goods regulations. Brightplus's thermolusters boast advanced properties such as enhanced durability, wear, and scratch resistance, aligning with circularity and sustainability principles to extend product lifespan and reduce resource consumption. Their use of sustainable materials and production processes contributes to environmental conservation, promoting a responsible and eco-friendlier product lifecycle. Brightplus engages in innovative R&D projects to transform sustainable packaging solutions, developing bio-based materials like LOIMU-C73[134], a biobased polyester, with advanced manufacturing processes for eco-friendly packaging. Collaborations on initiatives like 'Origin by Oceans' underscore their dedication to innovative and sustainable projects utilizing bio sources like algae-based biomass.[135]

4.4.2 Environmental impacts

The Brightplus coating product demonstrates a commendable commitment to environmental sustainability within the advanced coatings sector. Efforts to reduce VOCs are notable, with the adoption of alternative methods like powder coating. This approach utilises solid, fine particles instead of solvents, significantly minimising VOC emissions and aligning with circularity principles by reducing the environmental impact associated with VOC. Additionally, choosing single-layer coatings over multilayer alternatives promotes sustainability by minimising raw material use, enhancing recyclability, and reducing waste in the coating industry. Thinner coating layers not only offer economic advantages but also improve the flexibility of the coating process.

Emphasising recyclability is a key focus, with coatings designed for application on bio-based, biodegradable, recyclable, or compostable substrates. This ensures the recyclability of the entire package, aligning with CE principles and supporting a more sustainable and circular approach in the coating industry. The adoption of low-temperature coating processes, especially for paper and cardboard substrates, further enhances environmental benefits by minimising energy consumption, avoiding substrate darkening or yellowing, and contributing to overall energy efficiency and CE objectives within the coating industry.

Further environmental benefits can be seen from BrightBio®LOIMU[134] biopolymers which can be replaced with a wide range of plastics. For instance, LOIMU-C73 replaces an impressive 99.5% of fossil-fuel-based materials with biobased alternatives, while LOIMU-D11, LOIMU-D55, LOIMU-D75, LOIMU-K25, and LOIMU-K35 replace 68%, 80%, 85%, 75%, and 80% respectively. Even LOIMU-E30, with a 25% substitution rate, contributes to diminishing environmental impact. These replacements not only decrease carbon emissions associated with fossil fuel extraction and processing but also promote sustainability and support the transition towards a more renewable and eco-friendly production chain. These eco-friendly alternatives seamlessly integrate into customers' processes as convenient drop-in solutions, showcasing their adaptability and ease of adoption.

4.4.3 A case study of technological innovations

Introduction Paper coating played a vital role in improving both the visual appeal and practical utility of paper products. Traditionally, this involved the use of petroleum-based derivatives such as polyethylene, waxes, and fluorinated compounds to regulate properties like barrier resistance and wettability. Nonetheless, sustainability concerns persisted due to the reliance on non-renewable resources and harmful chemicals. Additionally, the limited recyclability of coated materials posed a significant threat to ecosystems. It was imperative to address these challenges to ensure the continued viability and eco-friendliness of the paper coating industry.[136]

Challenge Conventional coating processes often involved the use of non-renewable materials and chemicals, posing environmental concerns. Achieving a balance between providing effective protective coatings for wallpapers and carton packaging while minimizing the ecological footprint remained a significant challenge. Additionally, packaging polymers suffered from barrier properties which were required in many applications, especially in packaging materials for foodstuffs, cosmetics, drugs, etc., to protect the product inside the package from light, oxygen, and moisture, preventing contamination.[137] Replacing conventional with biodegradable polymers could pose challenges to barrier properties as the material could break down naturally over time, which might compromise their ability to provide good properties. Additionally, the coated materials needed to be easily recyclable, cost-effective, and had to address the growing demand for sustainable and circular solutions in paper coating for wallpapers and carton packaging.[136]

Solution Introducing a cutting-edge solution, Brightplus offered a biobased coating that surpassed traditional fossil-based counterparts like acrylics and polyvinyl alcohol (PVA). This innovative coating was not only durable and breathable, ensuring excellent surface protection, but it also added an extra layer of beauty and functionality to enhance the design of various items. Addressing three crucial sustainability challenges, Brightplus focused on transitioning from fossil fuel-based to more eco-friendly raw materials, extending the lifespan of coatings to reduce the demand for resources, and incorporating enhanced design features that encouraged prolonged item retention. By replacing fossil-based materials, extending coating longevity, and prioritizing design appeal, Brightplus developed a biopolymer composition from a porous substrate, polyester, and siloxane precursor, followed by pulverization into a powder. This powder, applied and cured on the substrate in a powder coating system, formed a packaging material with barrier properties, ensuring a water vapor transmission rate below 300 g/(m2-24 h) and aligning with CE principles by minimizing resource consumption and promoting extended product use.[138]

4.4.4 Key performance indicators (KPIs)

While specific data for estimating KPIs for Brightplus is currently unavailable, their recent achievement of winning the EcoVadis Silver Medal suggests commendable performance for the new company. This prestigious accolade highlights Brightplus' exceptional dedication to sustainability, positioning it among the top 25% of companies assessed by EcoVadis. It serves as a testament to the company's robust sustainability management system, responsible business practices, environmental stewardship, and adherence to ethical standards.[139]

Moreover, Brightplus Oy is intensifying collaboration with other technological partners through new national projects focused on carbon capture, biobased materials, and materials recycling. Their aim is to develop sustainable material applications for the circular economy. Recognizing the growing market for sustainable materials, particularly in protective packaging and thermal insulation, the companies are leveraging side-streams in material applications. This cooperation contributes to the principles of the circular economy and helps preserve limited resources.[140]

5 RESULTS AND DISCUSSION

This chapter provides a comprehensive analysis of the integration of CE principles within the ECI, detailing the environmental impacts, identifying implementation opportunities, and developing actionable policy and industry recommendations. This analysis focuses on the practices of key industry players such as BASF, Covestro, Hempel, and Brightplus Oy.

5.1 Current circular practices and integration of CE principles within the ECI

The European Coating Industry is witnessing a significant transformation as it embraces CE principles to enhance sustainability. Pioneers like BASF, Covestro, Hempel, and Brightplus Oy are leading this shift, each integrating CE into their operations uniquely. BASF has been a frontrunner, leveraging renewable feedstocks and pioneering innovative material cycles through its "Verbund" system, which optimizes production, energy flows, and waste management to minimize environmental impacts and boost resource efficiency. Covestro has taken significant steps by utilizing alternative raw materials and developing sustainable products, notably their polyurethane recycling technology. Hempel has concentrated on enhancing the lifecycle impacts of its products with its "Futureproof" strategy, aimed at optimizing product formulations for greater durability and reduced environmental impact. Brightplus Oy, though smaller, has effectively utilized its agility to innovate in biobased coatings, proving how niche players can significantly influence the industry’s sustainability. These companies not only respond to regulatory pressures but also capitalize on market demands for sustainable products, positioning themselves as leaders in sustainable industrial practices.

5.2 Environmental impacts and challenges of linear production in the coating industry

The traditional linear production model in the coating industry introduces several environmental challenges, such as substantial emissions of volatile organic compounds (VOCs), hazardous air pollutants (HAPs), significant energy consumption, and extensive waste generation. These issues are exacerbated by the reliance on non-renewable resources, an increasingly untenable situation under stringent environmental regulations and the global drive towards sustainability. For example, solvent-based coatings, which remain the industry standard, significantly contribute to VOC emissions, adversely impacting air quality and contributing to climate change. Additionally, the disposal of these products often results in significant hazardous waste, contributing to growing landfill issues.

5.3 Opportunities and best practices for implementing CE principles

The shift towards a CE offers numerous opportunities for the coating industry to mitigate the environmental impacts associated with the traditional linear model. Innovations like the adoption of water-based and powder coatings, as pioneered by Covestro, have dramatically reduced VOC emissions, and showcased how changes in product composition can decrease the environmental footprint. BASF’s "Integrated Process II" in automotive coatings is an example of innovative practice, reducing material usage and energy consumption, thereby minimizing GHG emissions. Enhancing material recyclability is also crucial. Hempel’s incorporation of high-performance hull coating and Brightplus’s development of recyclable biopolymer coatings exemplify how material innovations can foster circularity. Establishing closed-loop systems where waste materials are reintegrated into production cycles significantly reduces resource extraction and waste production.

5.4 Recommendations and guidelines for the investor

To promote a more sustainable and circular approach in the coating industry, a multifaceted strategy involving regulatory support, innovation incentives, collaborative efforts, and increased transparency is essential. Governments should enforce regulations that encourage the adoption of CE principles, such as stricter environmental standards and incentives for using renewable materials. Financial and non-financial incentives should be provided to encourage companies to invest in sustainable technologies and processes. Promoting collaboration across the value chain can enhance the sharing of best practices and foster innovations in sustainable materials and technologies. Partnerships among companies, academic institutions, and governments are crucial for breakthroughs in sustainability. Companies should be encouraged to disclose their environmental impacts and sustainability progress more transparently. This transparency can build consumer and stakeholder trust and drive broader industry shifts towards sustainable practices.

This chapter has addressed the research questions by detailing how CE principles are integrated into the ECI, the environmental impacts of current practices, and identifying both the opportunities for and challenges to implementing these principles. It concludes with strategic recommendations for various stakeholders, aimed at facilitating a transition towards a more sustainable and circular coating industry. Through these efforts, the industry can not only address its environmental impacts but also enhance its long-term sustainability and economic viability.

6 CONCLUSION

The integration of CE principles within the ECI has experienced dynamic shifts and innovations, with companies of various sizes adopting sustainable practices to address environmental challenges and regulatory demands. Larger companies have capitalized on their extensive resources to set industry standards, employing recycled and bio-based materials across broad application areas. In contrast, smaller firms have demonstrated adaptability by focusing on specific, innovative products to maintain competitiveness and long-term viability despite resource constraints.

The future success of the coating industry's transition to greater circularity hinges on several factors, including the development and adoption of renewable resources and environmentally friendly technologies. One of the significant challenges facing the industry is the adoption of PFAS-free coatings, spurred by stringent new regulations and the lack of a globally uniform definition of PFAS.[141] The European Chemical Agency (ECHA) published its PFAS restriction proposal on March 22, 2023,[142] further emphasizing the regulatory pressures. This scenario underscores the need for extensive research and development to innovate PFAS-free solutions across a broad application area. The industry must invest in these areas to meet environmental standards and drive economic viability in a rapidly evolving regulatory landscape.

Challenges such as rapid regulatory changes necessitate robust collaboration between industry players, research institutions, and policymakers to facilitate the scaling of CE practices and to foster transparency. There is an urgent need to innovate and integrate biobased and recycled materials, improve coating processes to decrease energy consumption, and prolong the functionality and lifespan of coatings. Such advancements will not only support compliance with evolving regulations but also ensure the coating industry's sustainable and economically viable future.

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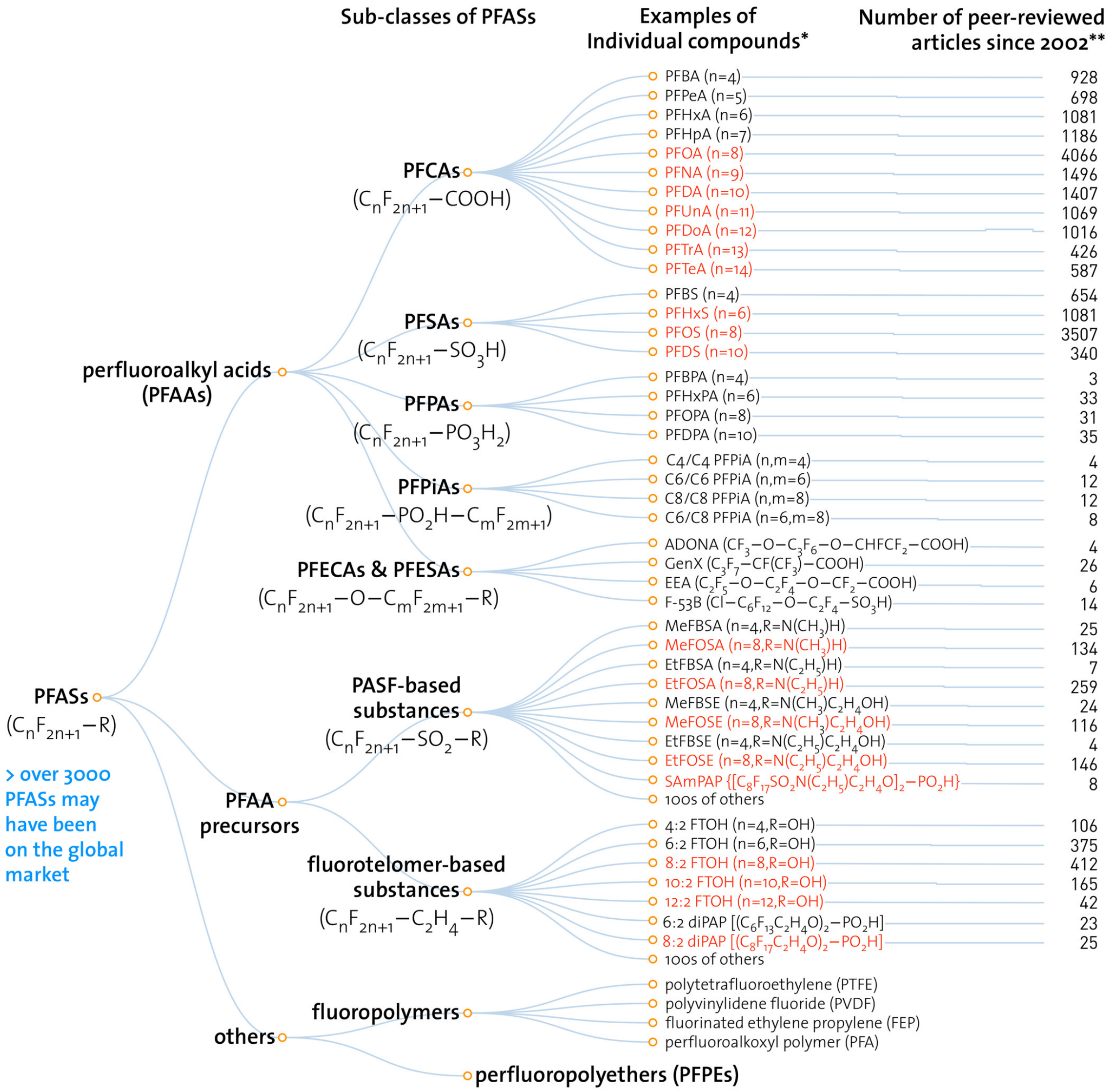
APPENDICES

Appendix 1. A detailed family tree of PFAS chemicals (with permission).[15]



* PFASs in **RED** are those that have been restricted under national/regional/global regulatory or voluntary frameworks, with or without specific exemptions (for details, see OECD (2015), Risk reduction approaches for PFASs. http://oe.cd/1AN).

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