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*Systematic Review*

# Engineering Innovations for Polyvinyl Chloride (PVC) Recycling: A Systematic Review of Advances, Challenges, and Future Directions in Circular Economy Integration

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**Abstract:** Polyvinyl chloride (PVC) recycling poses significant engineering challenges and opportunities, particularly regarding material integrity, energy efficiency, and integration into circular manufacturing systems. This systematic review evaluates recent advancements in mechanical innovations, tooling strategies, and intelligent technologies reshaping PVC recycling. An emphasis is placed on machinery-driven solutions—including high-efficiency shredders, granulators, extrusion moulders, and advanced sorting systems employing hyperspectral imaging and robotics. This review further explores chemical recycling technologies, such as pyrolysis, gasification, and supercritical fluid extraction, for managing contamination and additive removal. The integration of Industry 4.0 technologies, notably digital twins and artificial intelligence, is highlighted for its role in predictive maintenance, real-time quality assurance, and process optimisation. A combined PRISMA approach and ontological mapping are applied to classify technological pathways and lifecycle optimisation strategies. Critical engineering constraints—including thermal degradation, additive leaching, and feedstock heterogeneity—are examined alongside emerging innovations, like additive manufacturing and microwave-assisted depolymerisation, offering scalable, low-emission solutions. Regulatory instruments, such as REACH and Extended Producer Responsibility (EPR), are analysed for their influence on machinery compliance and design standards. Drawing from sustainable manufacturing frameworks, this study also promotes energy efficiency, eco-designs, and modular integration in recycling systems. This paper concludes by proposing a digitally optimized, machinery-integrated recycling model aligned with circular economy principles to support the development of future-ready PVC reprocessing infrastructures. This review serves as a comprehensive resource for researchers, practitioners, and policymakers, advancing sustainable polymer recycling.

**Keywords:** PVC recycling; polyvinyl chloride; digital twin; sustainable manufacturing; circular economy; chemical recycling; mechanical recycling; additive manufacturing; smart tooling; lifecycle optimisation

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## 1. Introduction

Polyvinyl chloride (PVC), a synthetic thermoplastic polymer, has been a pivotal material since its accidental discovery in 1872. PVC has been widely utilized in various industrial applications since its commercial introduction in the early 20th century. Recognised for its durability, corrosion resistance, and versatility, PVC, alongside other plastic types, is among the most produced polymers worldwide and also ranks as the third most widely produced material after cement and steel [1,2]. PVC is also recognized for its corrosion resistance, durability, glossy appearance, and ability to withstand environmental stressors [3]. The material's ubiquity in modern life underscores its importance. However, its widespread use presents significant environmental challenges, particularly concerning resource depletion and waste accumulation [4].

The disposal of end-of-life PVC contributes substantially to landfill overflow and marine pollution [5]. Additionally, incineration releases hazardous compounds, including dioxins, organo-chlorine substances, hydrogen chloride gas, and additives, thus posing environmental and health risks [6]. Recycling PVC offers a pathway for mitigating these impacts by ensuring resource conservation and waste minimization [7]. Furthermore, technological advances, such as in chemical recycling, have been instrumental in the making of recycled PVC that retains the same physical and chemical properties as virgin PVC, thus, making it suitable as a secondary raw material [8,9]. This advanced process thus aligns with circular economy goals that emphasize resource efficiency and waste reduction [10] and encourage policies and practices aimed at minimizing environmental pollution and conserving natural resources [10–12].

Moreover, sustainable manufacturing today must be understood as a multidimensional imperative aligned with the ESET framework, integrating economic, societal, environmental, and technological factors [13].

Despite these promising developments, the practical implementation of PVC recycling continues to face technological and economic hurdles. Challenges such as additive contamination, polymer degradation, and process scalability limit the efficiency of existing recovery systems. Challenges have been similarly recognized in low-carbon manufacturing (LCM) frameworks, where operational and supply-chain-level models seek to minimize $CO_2$ emissions through the linear optimisation of resource use [14]. Nevertheless, engineering innovations in mechanical, chemical, and feedstock recycling offer viable pathways for enhancing the recyclability of PVC within circular economy frameworks [15]. The pyrolysis technique, for example, makes it possible to recover PVC from contaminated PVC wastes due to the relative ease and low pollution of the process involved [16].

*Objectives of This Study*

This review systematically examines historical and contemporary practices in PVC recycling, with a specific focus on the role of artificial intelligence, additive manufacturing, and automation in enhancing recycling efficiency within circular economy frameworks. The specific objectives are as follows:

1. To trace the development of PVC recycling technologies and evaluate their environmental impacts across various historical phases.
2. To analyse the integration of advanced manufacturing systems guided by PRISMA protocols within PVC recycling processes and assess their contributions to circularity and process optimisation.
3. To evaluate the extent to which innovative engineering solutions improve resource efficiency and reduce waste in PVC recycling systems.
4. To identify existing challenges in PVC recycling and explore engineering solutions to address them.
5. To formulate evidence-based policy recommendations and outline strategic research directions that support the development of sustainable PVC recycling infrastructures.

In alignment with the objectives, this review addresses the following research questions:

1. How have PVC recycling methods evolved over time, and what are the key technological milestones that have shaped their development?
2. In what ways do advanced manufacturing technologies contribute to the efficiency and scalability of PVC recycling processes?

3. To what extent do current PVC recycling strategies align with circular economy principles, and how can system integration improve lifecycle optimisation?
4. What are the critical inefficiencies and environmental burdens associated with traditional PVC recycling methods, particularly regarding energy use, recovery rates, and material degradation?
5. What technological and regulatory gaps remain in integrating circular economy principles into advanced manufacturing systems for PVC recycling, and what research is needed to address them?

## 2. Background: Historical Development and Evolution of PVC Recycling

Polyvinyl chloride (PVC) has been widely used in industrial applications due to its durability, chemical resistance, and affordability. However, its end-of-life disposal poses significant environmental challenges, necessitating efficient recycling methods. Historically, PVC recycling efforts gained momentum in the 1960s, when concerns over plastic waste pollution led to early waste management initiatives. Initially, manufacturers focused on the in-house recycling of pre-consumer waste, while post-consumer recycling remained underdeveloped due to contamination issues and technological limitations [17,18]. By the 1970s, mechanical recycling emerged as a key strategy, driven by rising plastic waste generation and regulatory pressure. Despite improvements in sorting, cleaning, and reprocessing techniques, mechanical recycling faced challenges such as material degradation and the presence of hazardous additives [19]. More recent advancements have integrated chemical and feedstock recycling, aiming to recover high-quality PVC material as an end-product while mitigating environmental impacts. Moreover, recycling remains the final option for managing waste, protecting the environment, and benefiting from the energy produced in the process [20].

The diversity of PVC applications is illustrated in Figure 1 below, which highlights its predominant uses in Europe. Moulded profiles, pipes, and fittings make up the largest portion of PVC applications, while rigid plates, coated fabrics, and flexible tubes make up the smallest portion of applications.

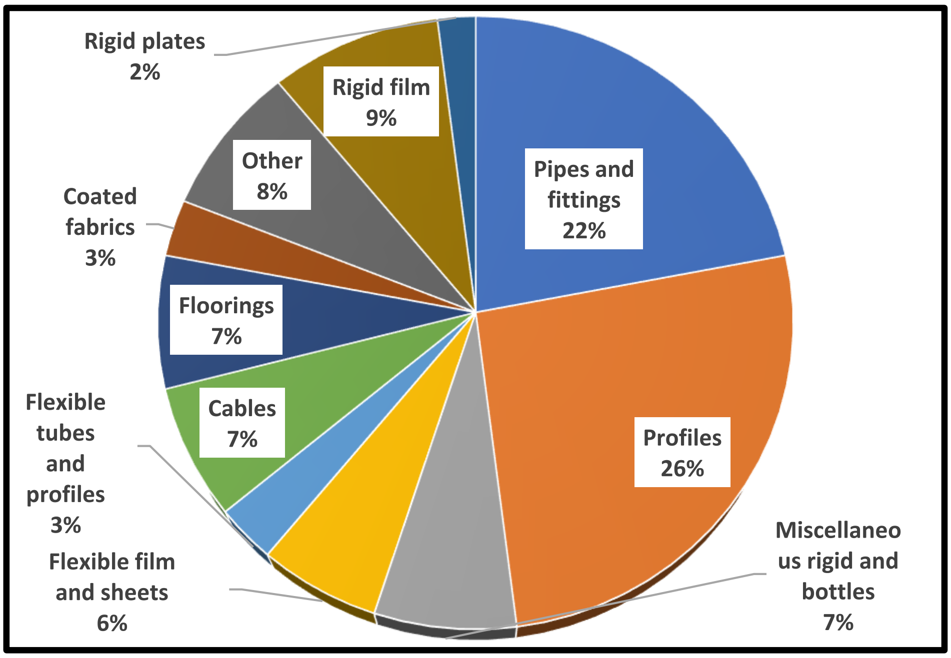


**Figure 1.** Distribution of total PVC use for different applications in EU [20].

*Milestones in Regulatory Frameworks for PVC Waste Management*

Regulatory frameworks have played a crucial role in shaping PVC recycling policies. The European Union's REACH, UK REACH, and Extended Producer Responsibility (EPR) directives have mandated restrictions on harmful additives, thereby promoting safer recycling practices [21,22]. Additionally, the Circular Economy Action Plan emphasizes closed-loop recycling systems, encouraging industries to design recyclable PVC products. While these regulations have improved waste management strategies, inconsistencies in the enforcement across continents, countries, and regions remain a barrier to widespread adoption [23].

## 3. Methodology

### *3.1. Materials and Methods*

This study employs a systematic review methodology incorporating PRISMA guidelines and ontology mapping. This methodological approach ensures a comprehensive and structured assessment of PVC recycling trends, challenges, and potential advancements.

This study's foundation integrates traditional systematic review with advanced knowledge representation techniques, aligning with both sustainability metrics and intelligent manufacturing research.

Incorporating insights from Low-Carbon Manufacturing (LCM) theory [14], the methodology further draws from linear programming (LP)-based operational models for quantifying carbon emissions at both the supply chain and shop-floor levels. These models complement ontological mapping by providing decision–support frameworks aimed at optimising energy consumption, enhancing resource efficiency, and reducing carbon intensity. This hybrid framework thus strengthens the evaluation of recycling practices and smart manufacturing innovations within a circular economy context.

The research methodology is structured as shown in Figure 2.

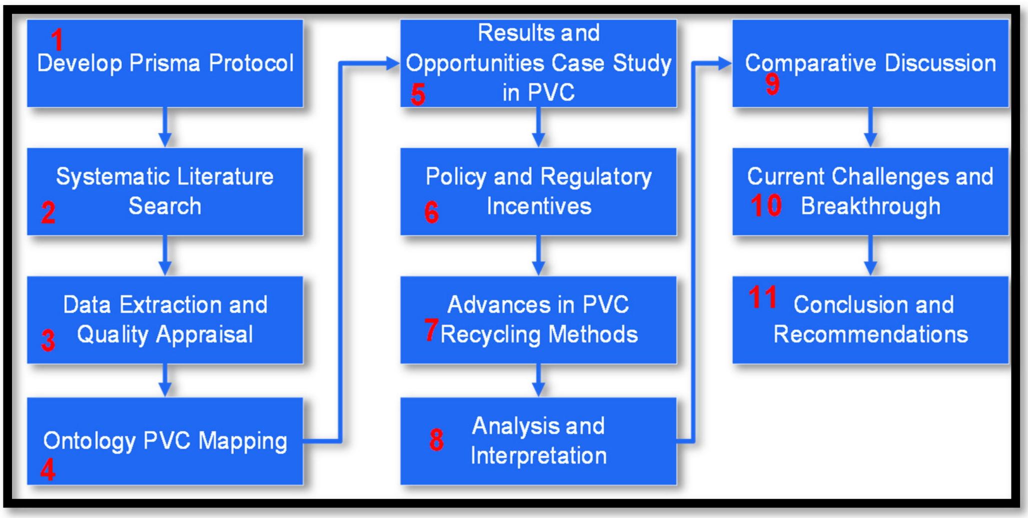


**Figure 2.** Applied systematic methodology used in this review, consisting of 11 sequential steps: (1) Develop PRISMA protocol, (2) Systematic literature search, (3) Data extraction and quality appraisal, (4) Ontology PVC mapping, (5) Results and case studies, (6) Policy and regulatory incentives, (7) Advances in PVC recycling methods, (8) Analysis and interpretation, (9) Comparative discussion, (10) Current challenges and breakthroughs, and (11) Conclusion and recommendations (Authors' own elaboration).

This study systematically addresses the research objectives by evaluating PVC recycling across its historical development, current challenges, and future opportunities. The methodology combines academic rigour and stakeholder relevance, aligning the analysis with current sustainability paradigms.

This study adopts a blend of PRISMA and ontology mapping approaches widely recognized for their comprehensive evaluative rigour. Following the PRISMA 2020 reporting standards for systematic reviews and meta-analyses, the methodology outlines a detailed review process, including article selection criteria, search strategies, data extraction, and data analysis procedures. This framework evaluates PVC plastic products, post-consumer waste challenges, and the effectiveness of recycling technologies. Additionally, this study critically examines recycling technologies and practices by way of addressing the environmental and sustainability implications of PVC waste management [24].

### 3.2. Systematic Literature Search Using PRISMA

The selection criteria aimed to ensure a comprehensive review by analysing a diverse range of peer-reviewed sources, case studies, and global practices related to PVC waste management and recycling. Databases such as PubMed Central, Google Scholar, ResearchGate, ScienceDirect, Web of Science, Springer Materials, and Scopus were utilized to provide a reliable foundation for the literature review.

Boolean operators facilitated keyword searches to retrieve relevant journals. The included search phrases were as follows:

TITLE-ABS-KEY: "PVC recycling" OR "circular economy" OR "sustainability" OR "historical trends" OR "future outlook"), "PVC recycling" AND "environmental impact" ("PVC recycling" OR "polyvinyl chloride recycling"), AND "circular economy" AND "sustainability" ("Environmental Pollution" OR "environmental impact" OR "ecological effects"), "PVC" AND "environment" ("PVC recycling" OR "plastic recycling" OR "polyvinyl chloride"), AND ("environmental impact" OR "ecological effects" OR "pollution"). These strategies ensured a broad and specific retrieval of topics such as PVC recycling, environmental impacts, circular economy principles, sustainability, technological innovations in PVC recycling, and future prospects. The results were refined across search engines to ensure precise and focused outcomes.

### 3.3. Search Parameters

This research focused on a 16-year period (2009–2024) and was justified by the VinylPlus initiative in 2011, which committed to recycling 800,000 tonnes of PVC annually by 2020. By 2019, VinylPlus had achieved 96% of this target, demonstrating the industry's commitment to sustainability and circular economy principles. Extending the range back to 2009 enabled an understanding of historical trends and balanced perspectives. The search process initially yielded 915 articles. Challenges such as data reliability and policy gaps highlighted the importance of understanding current PVC recycling practices.

### 3.4. PRISMA Assessment Protocol

Step 1: Preliminary Screening—titles and abstracts were critically reviewed to exclude unrelated studies. This reduced the pool to 457 articles.

Step 2: Suitability Assessment—articles were appraised for their alignment with study objectives, focusing on the following:

- PVC recycling methods and contributions to circular economy principles.
- Cutting-edge technologies, lifecycle assessment, and policy evaluation.
- Criteria for exclusion included duplicate studies, unclear results, low-quality methods, and outdated references. This step refined the selection to 120 high-quality articles.

Step 3: The final appraisal prioritised the relevance, innovation, and contributions to existing research gaps, with a particular emphasis on studies examining advanced recycling technologies and future developments. Following a rigorous selection process, 85 high-quality studies were identified as integral to the discussion and analysis of this research. These articles played a crucial role in shaping this study's analytical framework. Moreover, 101 supplementary articles enriched the broader contextual understanding of the research theme, providing valuable background insights that help inform the overall discussion.

### *3.5. Ontological Relationships Mapping in PVC Recycling and Circular Economy*

Ontological mapping, using Protégé, structured our knowledge about PVC recycling processes. This approach visualized interdependencies among recycling technologies, environmental policy, and system optimisation within a circular economy framework. Combined with LCM's operational models [14], the ontology's semantic networks are enhanced by incorporating energy flow constraints, machine-level carbon emissions, and supply chain decentralisation strategies, thus offering a simulation-ready platform for lifecycle-based decision-making [25].

Recent studies highlight ontology's efficacy in identifying barriers like material contamination and sorting inefficiencies. By integrating PRISMA and ontology mapping, the methodology supports the following:

- Identifying innovation areas;
- Refining data relevance and quality'
- Visualizing links between recycling technologies, CE principles, and policy interventions;
- Operational modelling for LCM, such as supply chain LP models [14], could complement ontological mapping by quantifying optimal recycling pathways based on energy and emissions efficiency.

## 4. Results: Opportunities and Case Studies in PVC Recycling

PVC has become an integral material in numerous industries, including construction, automotive, household, sports equipment, medical supplies, and textiles [23]. The global production of PVC has surpassed 350 million tons, with approximately 6.5 million tons produced annually in the EU-27, Norway, the UK, and Switzerland alone. This significant output underscores the urgent need for sustainable recycling strategies. Figure 3 illustrates the widespread applications of PVC, categorized by industry and product type, emphasizing the pressing issue of landfill waste due to inefficient and cost-prohibitive recycling methods [23].

PVC, composed of 43% petroleum by-products and 57% sea salt, offers unique properties such as water and fire resistance, longevity, and adaptability to various applications. Its flexibility and rigidity, along with colour variations, are achieved through specific additives, including lubricants, plasticizers, and pigments [18].

Recycling innovations are evolving toward a lower energy intensity and higher systemic integration, especially in smart tooling, chemical processing, and hybrid manufacturing platforms. The integration of LCM microfactory concepts [14] within additive manufacturing workflows presents decentralised, energy-efficient pathways for localised PVC recycling. For example, desktop manufacturing units are viable for converting PVC waste into printable feedstock, allowing a zero-waste design and minimal logistics overheads.

From a systems perspective, CNC strategies and sustainability matrices discussed in current sustainable manufacturing frameworks [13] offer potential benchmarking tools for PVC-specific recycling equipment. These can inform the design of smart extrusion machines, AI-integrated granulators, and modular reactor systems used in pyrolysis and supercritical fluid extraction processes.

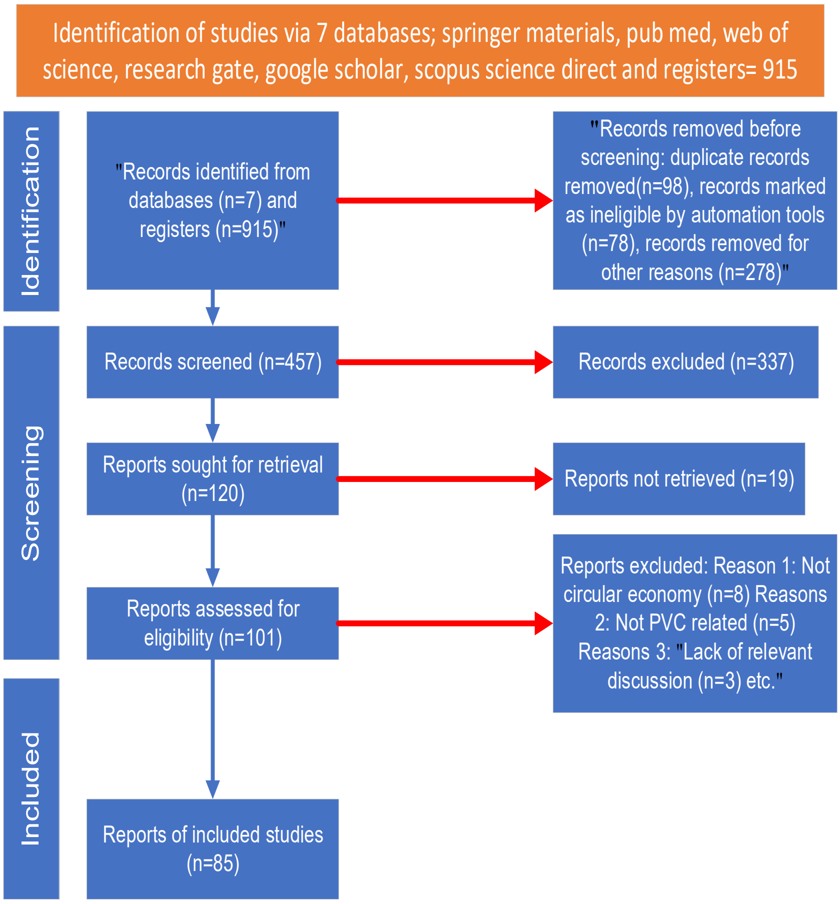


**Figure 3.** PRISMA flow diagram for systematic literature review [adapted and redrawn by the author based on [26]. The diagram illustrates the identification, screening, and inclusion stages used in selecting studies for this review. Adjustments were made to standardize terminology and enhance clarity, in accordance with the PRISMA 2020 guidelines. Following the systematic review, and in line with the PRISMA 2020 framework, additional data supporting this study were included in the checklist, and supplementary materials were provided in the supplementary list.

Furthermore, regulatory innovation can be enhanced by aligning lifecycle assessment protocols with energy flow modelling from LP-based LCM strategies. Such integration enables a robust evaluation of policy impacts on machine configurations, energy input-output metrics, and waste stream valorisation.

### *4.1. Technological Innovations in PVC Recycling*

The recycling of PVC presents significant opportunities for environmental sustainability, including resource recovery and waste reduction. Two major methods, chemical and mechanical recycling, have emerged as critical approaches to addressing contamination issues and improving material recovery [23].

The integration of energy-sensitive machining algorithms and eco-design strategies [13] can further strengthen process-level interventions in PVC mechanical recycling systems.

- Timeline of PVC Recycling Advancements

These milestones reflect the continuous advancement of PVC recycling technologies and policies, demonstrating the industry's efforts toward sustainability. Understanding the historical trajectory of PVC recycling is crucial for assessing its current landscape. Table 1 outlines key milestones in PVC recycling, highlighting significant developments that have shaped the industry and showing key industrial, regulatory, and technological milestones from 1872 to 2023.

**Table 1.** Timeline of PVC recycling advancements.

| Year | Milestone |
|---|---|
| 1872 | PVC first discovered [27] |
| 1920 | Commercial production and growing industrial applications [6] |
| 1980 | Introduction of mechanical recycling [19] |
| 2000 | Advancements in chemical recycling [23] |
| 2011 | VinyIPlus initiative launched [28] |
| 2021 | The official launching of VinylPlus 2030, reaffirming dedication to strive for a sustainable and circular future [28,29] |
| 2023 | 'The Vinyl Company' teamed up with the 'Responsible Care' initiative as partners of "A Sustainable Tomorrow", which focuses on efficient PVC material development to reduce its carbon footprint [30]. |

The information in Table 1 and Figures 4 and 5 depicts the different stages of evolution of PVC from its discovery through to its increase in popular uses to recycling and to more recent initiatives designed to meet sustainability goals.

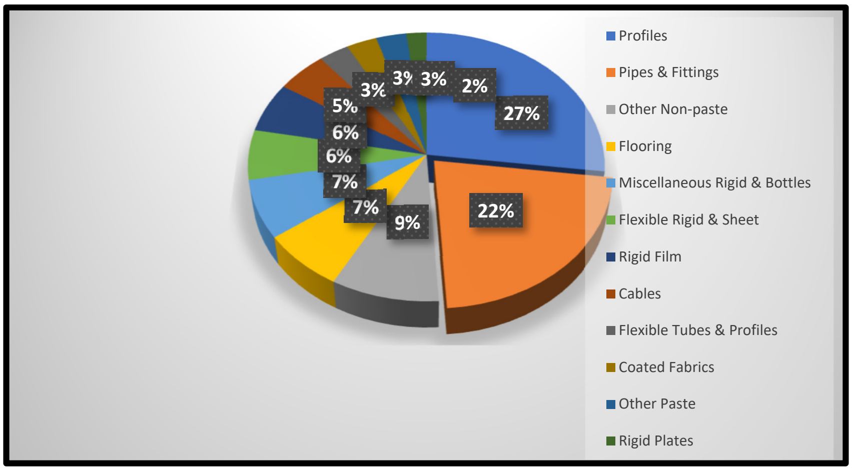


**Figure 4.** Global PVC applications by industry and product type [adapted and redrawn by the author based on [23].

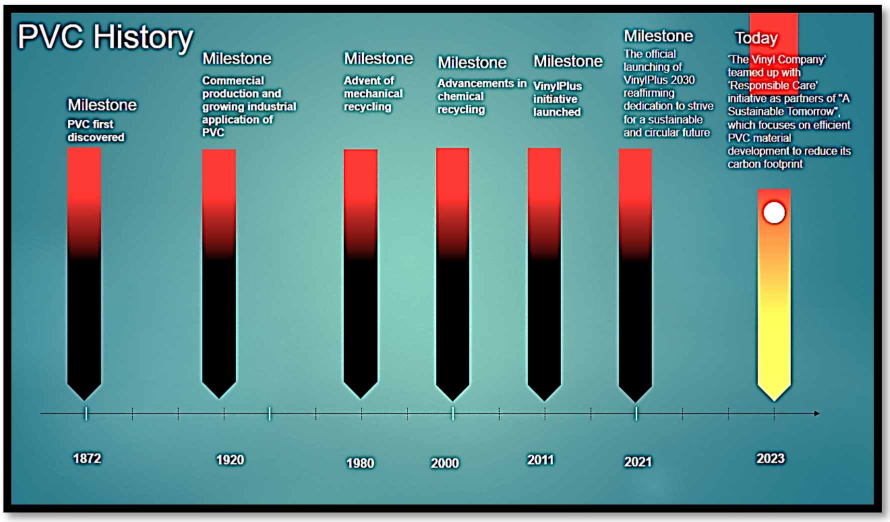


**Figure 5.** Diagram of PVC history with visual timeline of key milestones in the history of PVC recycling from 1872 to 2023. The diagram illustrates technological, industrial, and regulatory developments leading toward the modern circular economy agenda. (Adapted and elaborated by the authors based on Table 1 above).

- Chemical Recycling Techniques

Chemical recycling methods, such as pyrolysis, polymerization, and gasification, provide alternative solutions to PVC recycling challenges by converting waste into valuable raw materials or fuels. These methods reduce the dependency on virgin PVC and mitigate environmental issues associated with landfilling [31–34].

Pyrolysis uses thermochemical decomposition to break down the PVC waste stream to release by-products of wax, oil, gas, and solid residues. The process not only addresses environmental challenges but also recovers high-value raw materials [35]. Monomers are derived and used as a secondary raw material to reproduce PVC [36].

Gasification is a chemical treatment of PVC waste in the presence of air and steam, producing energy, syngas, and other chemicals, and derives monomers for reproducing new PVC with the same quality as the virgin material [36].

X-Ray Fluorescence (XRF) and Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) are not recycling methods themselves but serve as valuable support tools in the chemical recycling process by aiding in the identification of materials and contaminants in PVC [37]. Additionally, solvent-based closed-loop recycling enables the depolymerisation of PVC into monomers for re-polymerization into high-quality materials [38]. Integrating chemical recycling into circular economy frameworks significantly improves resource conservation and minimizes emissions, making it a vital component of sustainable recycling solutions [39].

- Advances in Mechanical Recycling

Mechanical recycling, characterized by shredding, washing, and re-granulating waste PVC, remains an important method due to its simplicity and lower environmental impact. This approach has effectively managed PVC waste from products such as cables, films, and bottles while preserving the material integrity [40].

However, challenges such as impurities and legacy chemicals, like DEHP, reduce the recycling efficiency. Advanced technologies, including hyper-spectral imaging and compatibilizers, enhance the purity and quality of recycled PVC [41,42]. Despite these challenges, mechanical recycling continues to play a critical role in managing both post-consumer and industrial PVC waste streams, and new innovations in machinery and technology are emerging that could change global recycling practices in the near future [43].

### *4.2. Integrating Recycling Methods into Circular Economy Principles*

The integration of chemical and mechanical recycling techniques within circular economy frameworks offers comprehensive solutions to PVC waste management. Innovations such as selective dissolution and advanced sorting technologies enhance recycling efficiency while reducing energy consumption and greenhouse gas emissions [22,44].

For instance, mechanical recycling has gained traction in regions like the EU due to its economic viability, while emerging chemical recycling methods show promise for large-scale applications [45]. By improving recycling operations using modern technologies, like artificial intelligence and digital twins, and adopting CE principles, PVC waste can be transformed into valuable feedstock, thereby fostering resource conservation and sustainability [46].

The integration of energy-sensitive machining algorithms and eco-design strategies [13] can further strengthen process-level interventions in PVC mechanical recycling systems.

### *4.3. Policy and Regulatory Incentives*

Despite its widespread use, PVC recycling has historically suffered from limited regulatory support. The absence of robust policies addressing hazardous additives and end-of-life disposal has hindered recycling progress [23]. For example, during the 1980s and

1990s, mechanical recycling faced numerous technical and regulatory challenges, leading to minimal recycling rates [20].

Recent advancements, such as the European Union's REACH regulation, mandate the removal of harmful additives, like di (2-ethylhexyl) phthalate (DEHP), before recycling, ensuring safe and sustainable practices achievable through the continuous improvement in and application of modern innovative technologies [21,47].

Extended Producer Responsibility (EPR) policies have also emerged, requiring manufacturers to take accountability for the entire lifecycle of their products [22].

Government incentives, including tax breaks and subsidies for recycling infrastructure, further support PVC recycling efforts. These measures reduce financial barriers for industries, fostering participation in sustainable initiatives [48]. Additionally, public education campaigns raise awareness about the environmental benefits of recycling, encouraging community engagement and participation [23].

### *4.4. Case Study: Successful PVC Recycling Initiatives*

PVC recycling initiatives worldwide demonstrate the potential for resource recovery and sustainability.

Programs such as VinylPlus have successfully promoted recycling by fostering industry partnerships and implementing advanced recycling technologies. In 2020, VinylPlus recycled approximately 550,000 tonnes of PVC, aligning with the European Commission's circular economy goals [49].

Technological innovations, including the Vinyloop process and microwave-assisted recycling methods, have shown significant promise in improving recovery rates and reducing pollution [50]. Additionally, solvent-based procedures recover high-value materials, like copper from PVC-coated wires, supporting the economic feasibility [51].

### *4.5. Challenges and Prospects*

Despite advancements, PVC recycling continues to face challenges, including contamination, hazardous additives, and inconsistent regulatory frameworks. Mechanical recycling often struggles with maintaining a high material quality, while chemical recycling technologies face scalability issues [52].

Future efforts must focus on developing innovative recycling technologies, enhancing regulatory compliance, and fostering international collaboration to achieve the full potential of PVC recycling within circular economy frameworks [23,53].

## 5. Advances in PVC Recycling: Engineering and Technology

Due to the challenges associated with conventional PVC recycling methods, such as mechanical and thermal recycling, innovative manufacturing processes are essential to overcome these limitations and achieve circular economy objectives. These innovative manufacturing processes enable the derivation of raw materials from PVC waste, which have the same characteristics as virgin raw materials. The derived raw materials can be used either for manufacturing new PVC products, which technically implies that the PVC is being recycled, or they can used for other purposes, such as fuel or the manufacturing of alternative products.

### *5.1. Innovative Manufacturing Processes Used in PVC Recycling*

The following innovative technological processes are used to enhance PVC recycling:

- Chemical recycling;
- Additive manufacturing (3D printing);
- Supercritical fluid extraction (SFE);

- Microwave-assisted recycling;
- Electrochemical recycling;
- Biological recycling;
- Dissolution and extraction;
- Transforming PVC into a nanostructured catalyst support;
- Sorting with electromagnetic waves;
- Flotation with surfactants;
- Pre-treatment using reagents;
- Pre-treatment using Fenton reaction;
- Pre-treatment with thermal heat treatment (mild and microwave);
- Pre-treatment with corona discharge;

The following are true recycling processes mentioned above when used with depolymerized feedstock. In contrast, methods such as product reshaping without altering molecular structure represent reuse or repurposing.

- Chemical Recycling

Chemical recycling effectively manages impure and heterogeneous PVC waste streams by depolymerizing PVC into its original monomers through processes such as chemolysis, glycolysis, hydrolysis, pyrolysis, and gasification [54]. These monomers can be used to produce new PVC products or fuels [55]. While chemical recycling produces high-quality outputs equivalent to virgin PVC, it remains costly and energy-intensive, with limited scalability.

- Additive Manufacturing (3D Printing)

This process involves shredding PVC waste into a filament or powder for use in creating products via 3D printing. The material is added layer by layer to form items based on digital designs [43,53]. This approach ensures zero waste and a closed-loop system, facilitating creative and customized designs [23]. Despite its benefits, limitations in mechanical properties and the need for further research constrain its practical application.

In line with devolved manufacturi1ng (DM) models [14], additive manufacturing enables distributed, low-emission PVC reprocessing infrastructures, reducing logistics-based carbon footprints.

- Supercritical Fluid Extraction (SFE)

SFE uses supercritical fluids, such as $CO_2$, to extract plasticizers from PVC, thereby enhancing the recycling process [3,54,56]. Although environmentally friendly and capable of producing high-quality outputs, the process involves complex operations and requires high-pressure equipment [54,56]. Figure 6 illustrates the process which produces purified PVC as an end product where plasticizers have been collected separately.

- Microwave-Assisted Recycling

Microwave technology selectively heats PVC polymer chains, breaking them down into monomers. This process is energy-efficient and environmentally friendly but requires expensive equipment and may emit hazardous substances [57–59]. Figure 7 illustrates the complex process with the resultant monomers being collected in a jar (item 4).

- Other Innovative Recycling Techniques gaining traction are as follows:
    1. Electrochemical Recycling: employs electrochemical reactions for high-purity PVC recovery [60].
    2. Biological Recycling: Uses enzymes or microorganisms for the environmentally friendly degradation of PVC waste [61]. It is also known as ‘biodegradation’ or ‘enzymatic degradation’ process.

3. Dissolution and Extraction: selectively dissolves PVC using sustainable solvents [62]. It is used to extract and purify PVC from waste streams for use in making new products.
4. Nanostructured Catalyst Support: converts PVC into nanostructured materials for catalytic reactions [63,64]. It is an innovative, environmentally friendly process that enhances catalytic reactions.
5. Advanced Sorting Technologies: employs electromagnetic waves in an advanced sensor technology to separate PVC from mixed waste streams [65].

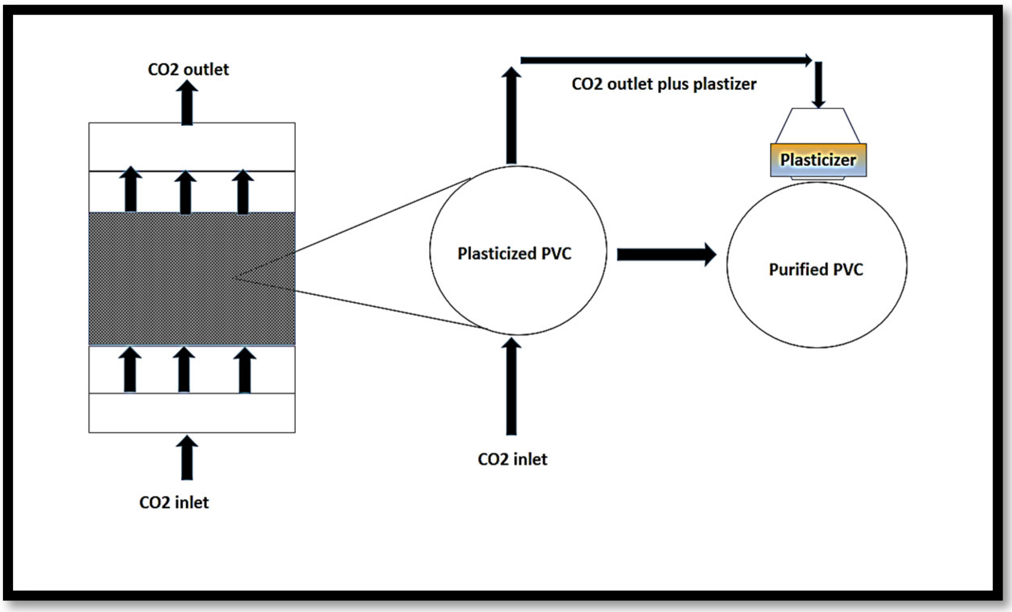


**Figure 6.** Illustration of SFE of PVC using $CO_2$; show the carbon dioxide $CO_2$ inlet as a treatment agent that passes through the plasticized PVC, selectively dissolves and extracts plasticizer molecules without affecting the PVC's chemical structure. The $CO_2$ now carrying the removed plasticizers, exits through the outlet and proceeds to a separation stage, where the plasticizers are collected, leaving behind purified PVC material. Diagram has been redrawn by author based on [56].

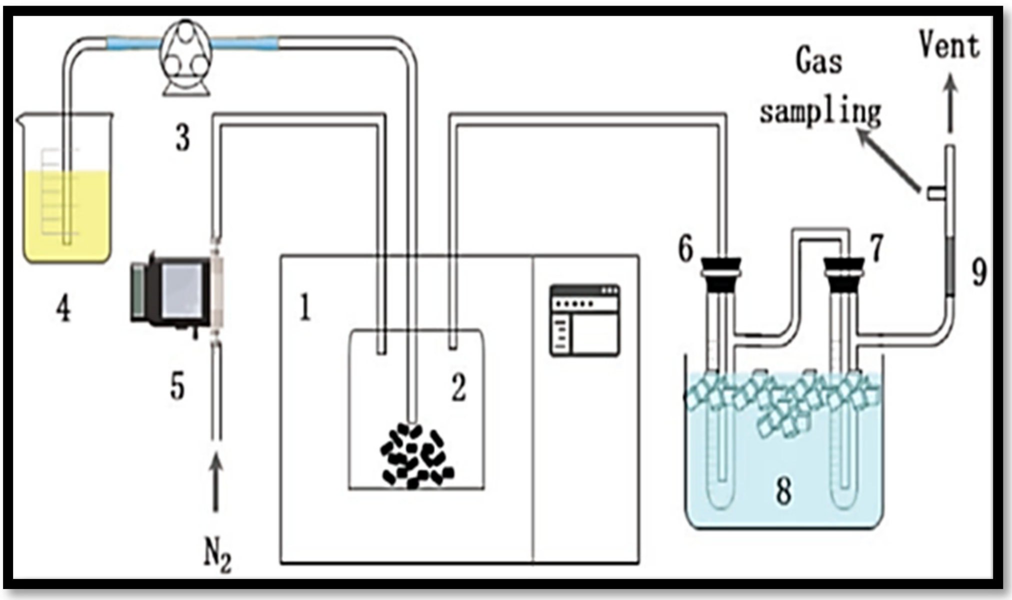


**Figure 7.** Schematic diagram of experimental setup for continuous pyrolysis process: (1) microwave oven; (2) quartz reactor; (3) peristaltic pump; (4) feedstock; (5) gas flowmeter; (6, 7) cold traps; (8) ice-water bath; and (9) cotton wool filter [adapted from [58].

6. Pre-Treatment Techniques: prepares PVC waste for recycling through methods such as the Fenton reaction, thermal heat treatment, non-thermal plasma technology, reagents, or corona discharge [64,66,67].
7. Flotation with surfactants: This technique enhances flotation when used in the recycling process. It involves the addition of surfactants to increase the efficiency in separation [57,67].

### 5.2. Integration of Sustainable Practices in PVC Manufacturing

Integrating sustainable practices requires blending conventional and modern recycling methods to mitigate individual challenges. The following processes are examples:

1. Catalytic Pyrolysis: reduces energy consumption and enhances the output quality [64,68,69].
2. Microwave-Assisted Pyrolysis: combines microwave technology with pyrolysis to degrade PVC waste [58,59].
3. Plasma Pyrolysis: converts PVC waste into syngas for hydrogen production and turbines [70].
4. Plasma-Enhanced Gasification: improves the output quality by minimizing unwanted by-products, such as tar and char [70–73].

- Low-Emission Manufacturing Technologies

Innovative recycling technologies aim to reduce environmental impact and conserve resources by minimizing greenhouse gas emissions. Emission reduction remains a key goal for sustainable PVC recycling systems [67].

- Material Substitution and Additives for Recyclability

Plasticizers and stabilizers enhance PVC's flexibility, durability, and processing stability, and challenges posed by these additives are being addressed through solvent-based extraction methods, enabling an improved recyclability [6,23].

### 5.3. Innovations in Production Machines and Tooling

Technological advancements in PVC recycling machinery improve efficiency and align with circular economy goals.

For example, PVC can be automatically sorted from waste using robotics and AI technology [74].

Furthermore, the advancement in chemical recycling has ensured a reduced dependence on virgin polymers by making it possible to derive high-quality virgin-like monomer materials from recycled waste [58].

These innovations from recent technological advancements are progressively leading toward the attainment of a circular economy.

- Machinery Optimized for Recyclable Materials

Recycling operations involve the use of machines specially optimized to perform specific operations in the different stages of recycling. The production line in the recycling process is made up of sorting machines, shredder machines, compression machines, extrusion machines, and granulator machines [75].

1. Sorting machines: Separate PVC from mixed waste streams [65]. This is illustrated in Figure 8.
2. Shredders: Reduce PVC waste into manageable sizes [76]. Figure 9 illustrates the shredding process.

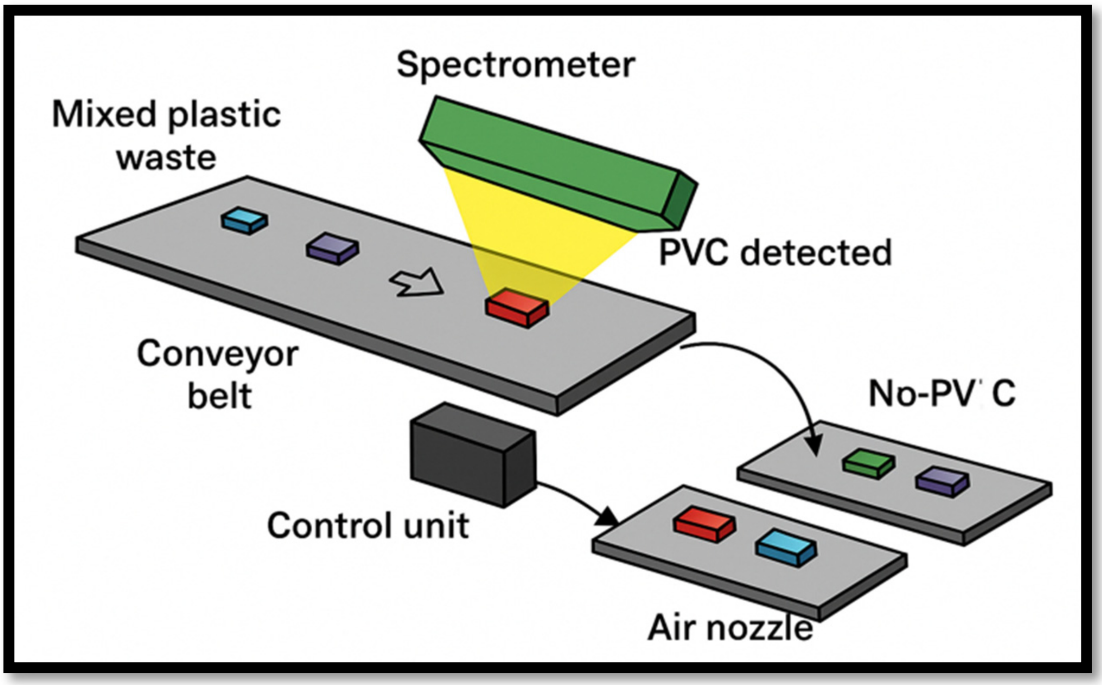


**Figure 8.** An illustration of automated PVC plastic waste recycling. This figure has been conceptually redrawn by the author and is adapted from the original design in [65].

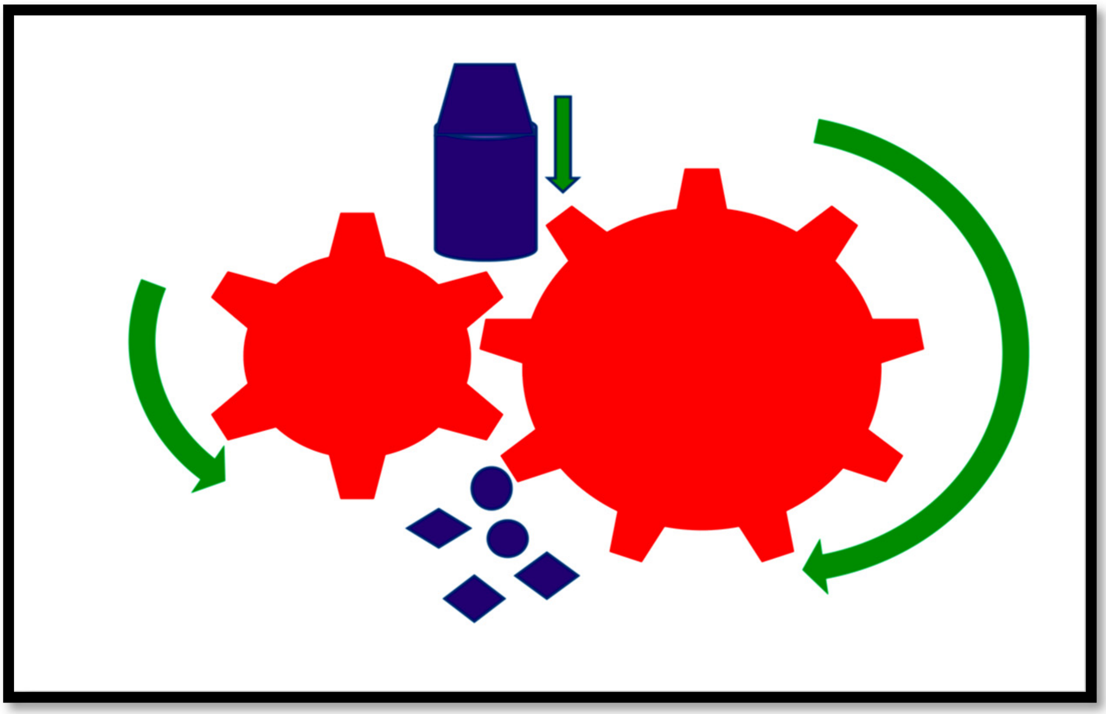

**Figure 9.** A diagrammatic illustration of a 2-shaft shredder This figure has been conceptually redrawn by the author and adapted from the original design in [76].

3. Granulators: further crush PVC into consistent sizes [74,75].
4. Extruders: transform PVC into sheets, films, or structural parts [43].
5. Compression machines: Mould PVC into desired shapes at controlled temperatures [46]. Figure 10 illustrates the process of the compression moulding of PVC.

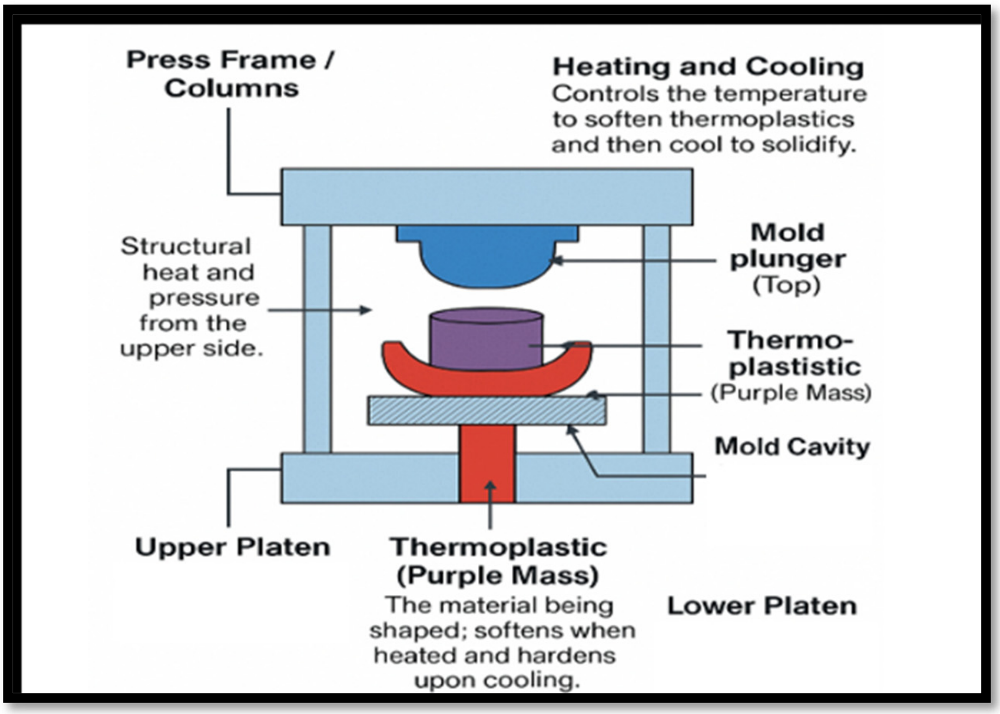


**Figure 10.** Illustration of compression moulding of recycled plastic. This version has been redrawn by author, based on [77].

- Smart Tooling for Sustainable Manufacturing

Smart tooling incorporates advanced technologies, such as AI, Big Data analytics, and cyber–physical systems, to optimize PVC production and recycling processes. These innovations support zero-defect production and sustainable practices [78,79].

Embedding energy flow monitoring into recycling machinery aligns with current CNC-based sustainability metrics that assess the machine efficiency and lifecycle impacts [13].

### *5.4. Systems Integration for Sustainable Outcomes*

Systems integration in PVC recycling and re-manufacturing is important for the attainment of sustainable development and a circular economy because a synergistic arrangement will ensure efficiency in energy and material usage as well as cost savings and information sharing.

Two aspects in the adoption of an integrated system are represented by the use of 'digital twins' and other automated technologies and machines in the production and recycling processes.

- Digital Twin and Industry 4.0 Applications in PVC Recycling

Digital twins are a computer software model of a physical thing, process, or system. It is a virtual representation of something in the physical world, such as a car, an office, or even an entire city, and is used to connect the physical world to the digital world [46,80].

The integration of Industry 4.0 technologies, particularly digital twins, offers new possibilities for optimizing PVC recycling processes. A digital twin is a virtual model of physical recycling systems, enabling real-time monitoring and predictive analytics to enhance efficiency. In PVC recycling, digital twins facilitate data-driven decision-making, such as optimizing sorting accuracy, minimizing material loss, and forecasting maintenance schedules for recycling equipment [80,81]. For instance, AI-driven digital twins in mechanical recycling plants can improve the contamination detection, reducing the reliance on manual sorting. Additionally, integrating IoT sensors in PVC processing units can provide insights into energy consumption, ensuring that sustainability metrics are met [82]. These innovations align with circular economy goals by improving resource efficiency and reducing waste during recycling operations.

- Automation in Recycling and Manufacturing Processes

Automation addresses the growing generation of PVC waste by enhancing the recycling speed and efficiency.

The rate at which PVC wastes and other plastic wastes are being generated has drastically increased in direct proportion to the global population growth because of the per capita consumption rate in recent times [48].

In order to cope with this drastic increase in the generation of plastic waste, the means of waste management and recycling have been consistently developed and enhanced by automation so as to manage waste as fast as it is being generated [72].

Therefore, continuous innovations are making recycling processes faster, easier, and more automated, thereby reducing the reliance on finite resources and promoting sustainable practices [72].

## 6. Analysis and Interpretation

To systematically analyse the research data from both quantitative and qualitative perspectives, this section presents the results of ontology-based data mapping and representation. These results are instrumental in examining the evolution, trends, and impacts within the field of PVC recycling. The application of the Protégé ontology tool is intended to address the research questions effectively by integrating data from both analytical dimensions. This mixed-method approach ensures that quantitative findings are reinforced by qualitative insights, thereby enhancing the depth and validity of the research outcomes.

*PVC Classes on Innovative Manufacturing Technologies*

The innovative manufacturing technologies query results (Figure 11) provided key points on the ontology domain which are related to subclasses such as the following:

- Digital twin applications;
- Low-emission technologies;
- Smart tooling.

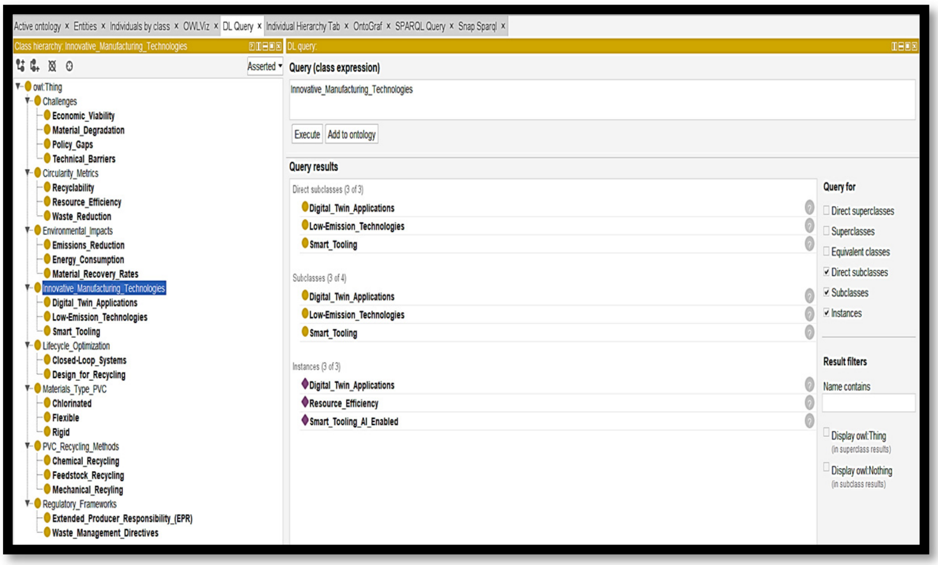


**Figure 11.** DL Query results on PVC classes innovative manufacturing technologies [83].

The results indicate that innovative manufacturing technologies focus on resource optimisation. It also shows the targeting of sustainability by reducing emissions and emphasizes new technologies that are intelligence-enable, especially AI-enabled, and tools for advanced manufacturing processes.

The relationship of the ontology hierarchy connects innovative manufacturing technologies to have a good relationship with wider characteristics, such as sustainability, efficiency, and smart-enabled processes, supporting their alignment with circular economy principles.

- PVC Classes on Lifecycle Optimisation

The lifecycle optimisation query results (Figure 11) provided direct subclasses and relationships, such as the following:

- Closed-loop systems;
- Design for recycling.

These subclasses underscore the design and operational systems intended to achieve a closed-loop cycle. They depict where resources and products are continuously reused or recycled, aligning with circular economy principles, while showing how strategies are aimed at designing products with the end-of-life PVC recycling process in mind to support materials recovery and a sustainable product lifecycle management.

The subclasses also show the relationship between closed-loop systems and designs for recycling which are interconnected, while the hierarchy contributes to the development of the PVC circular economy. Figure 11 illustrates the hierarchy and relationships generated from Protégé.

The ontology structure focuses on systematic levels, which are practical strategies towards a PVC circular economy, and lifecycle optimisation with the inclusion of the instances of, for example, designs for recycling products, which show that the ontology is granular enough to represent real-world industry applications to achieve sustainability goals.

- PVC Classes on PVC Recycling Methods

The PVC recycling methods query results (Figure 12) provided direct subclasses and instance such as the following:

- Chemical recycling;
- Feedstock recycling;
- Mechanical recycling.

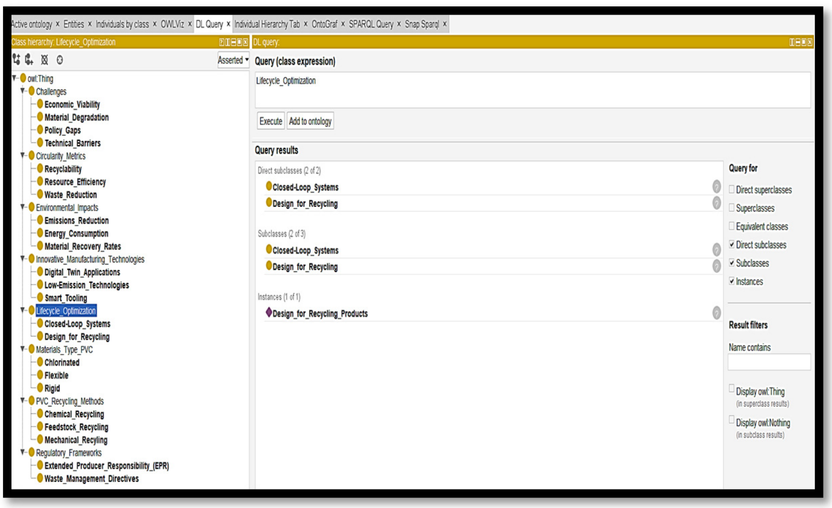


**Figure 12.** DL Query results on PVC classes lifecycle optimisation [83].

The direct subclasses indicate recycling methods that show the breaking down of PVC, which cannot be properly handled due to contamination issues, or waste by mechanical recycling.

Feedstock recycling refers to the conversion of PVC waste into raw materials (feedstock) for use in other industrial manufacturing processes while physical recycling involves converting PVC waste into new products without altering the material's chemical structure.

Processes related to the subclasses, such as chemical supercritical $CO_2$ treatment, align with chemical recycling but are also associated with feedstock recycling pilot programs.

The PVC hierarchy ontology structure classifies recycling into three subclasses, supporting the comparative analysis of methods based on efficiency, scalability, and environmental impact. The subclasses highlight cutting-edge recycling technologies that are essential for handling complex PVC waste while aligning with circular economy goals.

The query results also provided an ontology structure that shows the validation of feedstock recycling as theoretical frameworks for real-world industry applications, which could be assessed as the best method for its sustainability and feasibility of supporting and enhancing circular economy principles in specific contexts (e.g., low emissions, high recyclability). Figure 13 clearly displays diagrammatically how the recycling technologies are classified.

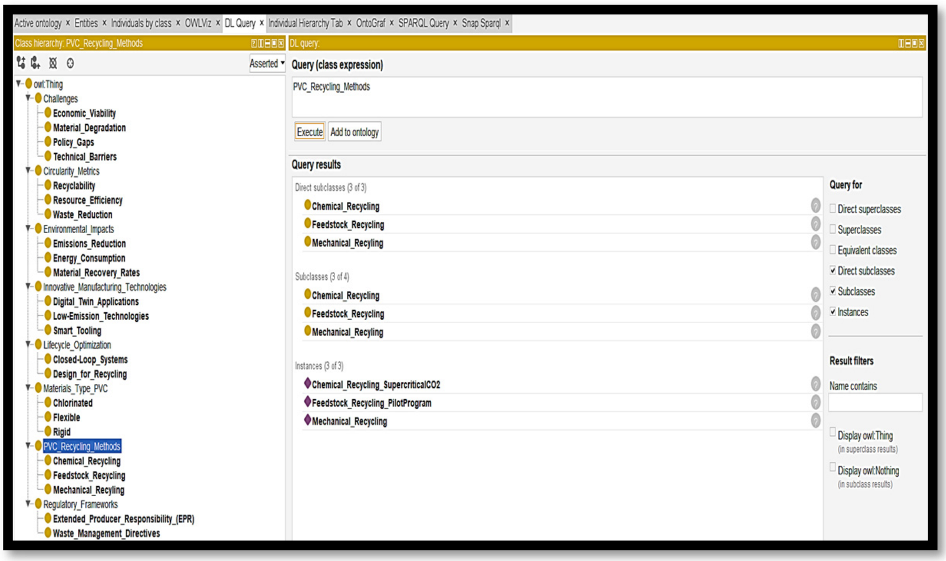


**Figure 13.** DL query results on PVC classes recycling PVC methods [83].

Future simulation environments for PVC circular systems could benefit from integrating LP-based operational models from LCM research, thereby providing quantifiable benchmarks for ontology-based system configurations [14].

## 7. Discussion: Circular Economy Perspectives for PVC Recycling

### *7.1. Transitioning PVC Recycling into a Circular Economy Framework*

The shift from a linear to a circular economy for PVC recycling is critical for resource efficiency and sustainability. Traditional PVC recycling has relied predominantly on mechanical processing, which, while reducing waste, leads to material degradation over multiple cycles. A circular economy approach aims to close the material loop by maximizing recovery, extending product lifecycles, and minimizing waste generation [12,28].

This section discusses how lifecycle optimisation, policy mechanisms, and technological advancements contribute to improving PVC recycling. By integrating circular economy strategies, the industry can reduce its dependence on virgin materials, lower emissions, and enhance regulatory compliance.

Figure 14 presents a comparative overview of the closed-loop economy in relation to the linear and reuse economies. While the linear and reuse models may be considered in situations where material recyclability is limited, the closed-loop and reuse approaches offer practical benefits for the management of and reduction in PVC waste. Both contribute to improved sustainability outcomes by promoting material retention and minimizing environmental impacts [84,85].

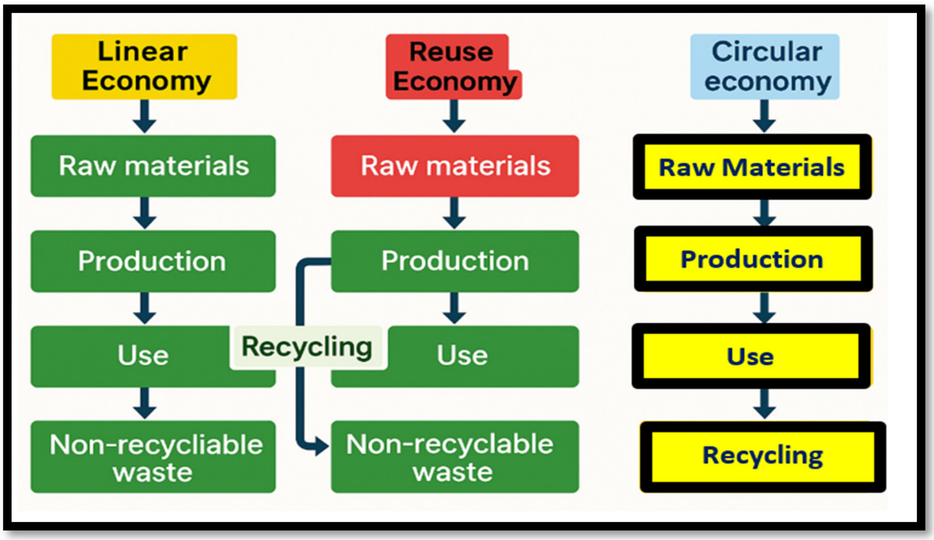


**Figure 14.** Schematic and components of linear, reuse, and circular economies (recycling). Redrawn and modified by author based on conceptual structure outlined in [86].

### 7.2. Strategies for Achieving a Closed-Loop System

- Design for Recycling

Enhancing recyclability at the design stage ensures higher material recovery rates and reduces the environmental impact. Selecting non-toxic additives, optimizing polymer structures, and engineering products for easy disassembly are key strategies in circular PVC production. Improved polymer formulations and biodegradable plasticizers enable repeated recycling without a significant loss of mechanical properties, addressing concerns about material degradation [87]. This links to the research question regarding the lifecycle optimisation by presenting design-based solutions for PVC sustainability.

- Extended Producer Responsibility (EPR)

EPR policies transfer the responsibility for post-consumer PVC waste from end-users to manufacturers, encouraging sustainable material management. By implementing take-back schemes and promoting recyclable designs, manufacturers help facilitate closed-loop recycling. The VinylPlus initiative in the European Union is an example demonstrating how regulatory incentives can drive sustainable industry practices [28,29]. Addressing the research objective of policy frameworks, this section highlights the role of regulatory instruments in advancing circular economy principles.

### 7.3. Circularity Challenges and Barriers

Despite its benefits, transitioning PVC recycling to a circular economy model presents challenges, which include the following:

- Technological Barriers: Current mechanical recycling methods result in polymer degradation, limiting recycling prospects. Chemical recycling offers a solution but remains economically unscalable.
- Regulatory Variability: inconsistent global policies create inefficiencies in cross-border waste management and hinder large-scale adoption.
- Market Hesitancy: industries often resist using recycled PVC due to concerns about quality and processing stability, impacting the demand.
- Economic Constraints: high capital investment requirements for advanced recycling infrastructures pose financial risks for smaller enterprises.

This connects to the research question on identifying inefficiencies in existing recycling systems, offering insight into technical and regulatory barriers impeding circular adoption.

Transitioning to a circular economy model for PVC recycling requires addressing both technical and policy challenges. The primary barriers include an inadequate waste collection infrastructure, a lack of standardization in recycling protocols, and consumer resistance due to perceived quality differences in recycled products [23,41]. Furthermore, inconsistent regulatory frameworks across regions hinder the development of a unified recycling strategy.

To mitigate these challenges, policymakers must establish clear guidelines for PVC recyclability standards, ensuring consistency in the product quality and safety. An increased investment in public awareness campaigns can also promote consumer trust in recycled PVC products, facilitating a broader market adoption.

### *7.4. Opportunities and Benefits for Circularity in PVC Product Lifecycles*

Shifting towards closed-loop recycling significantly reduces environmental impacts by cutting $CO_2$ emissions, lowering energy uses, and diverting waste from landfills. Studies indicate that improved mechanical and chemical recycling systems can reduce greenhouse gas emissions from PVC production by 30%, highlighting their role in mitigating climate change [88], addressing the research question concerning environmental impacts and the effectiveness of recycling strategies.

Advancements such as AI-driven sorting systems, digital twins for process optimisation, and solvent-based purification techniques improve the PVC recycling efficiency. These technologies enhance recovery rates, reduce contamination, and enable the production of higher-quality recycled PVC [58], addressing the research question of how innovative manufacturing and engineering solutions can enhance recyclability.

### *7.5. Future Directions in PVC Recycling Innovations*

Future research must focus on scaling cost-effective recycling solutions, optimizing material designs for repeated use, and integrating regulatory frameworks to standardize PVC recycling processes globally. Digital technologies, such as block-chains for supply chain transparency and AI-driven quality control, offer promising pathways for enhancing material traceability and efficiency. Strengthening collaboration among industry stakeholders, policymakers, and researchers will be key in achieving a fully circular PVC industry.

By aligning with circular economy principles, PVC recycling can transition from a waste-intensive model to a sustainable, resource-efficient system. This section synthesizes technological and regulatory insights to propose actionable future directions.

Innovations such as smart sorting systems, AI-powered quality control, and blockchain-based traceability platforms represent potential for revolutionizing PVC recycling. These technologies can enhance the transparency in material sourcing, reduce contamination risks, and optimize resource allocation across the recycling value chain. Additionally, further research into bio-based additives for PVC formulation could improve its recyclability and environmental footprint [89].

By aligning technological advancements with circular economy principles, the PVC industry can achieve long-term sustainability goals while maintaining economic viability. Strengthening collaborations between researchers, policymakers, and industry stakeholders will be crucial in driving further innovations in PVC recycling.

This study also underscores the pivotal role of engineering innovations and smart technologies in transforming PVC recycling practices toward a more sustainable, circular, and intelligent manufacturing paradigm. By synthesising insights from LCM frameworks [14] and sustainable manufacturing tools [13], this research presents an interdisciplinary approach to designing low-carbon, resource-optimised recycling systems.

The key takeaways are as follows:

- The integration of ontological mapping and LP-based operational models enhances the system-level understanding of energy and material flows.
- Desktop manufacturing and devolved supply systems provide viable models for decentralised PVC recycling infrastructures.
- Smart tooling and CNC energy flow analytics offer practical benchmarks for machine performance and environmental compliance.

Future work will also focus on the simulation-based validation of integrated ontological–operational frameworks and the development of a digital twin system for real-time lifecycle optimisation in PVC reprocessing facilities. Moreover, the implementation of sustainable manufacturing matrices will support the continuous performance assessment of recycling technologies in line with net-zero targets.

### *7.6. Addressing Gaps and Future Directions in PVC Recycling Innovation*

There are areas not adequately explored in the quest for a circular economy through PVC recycling, such as the use of digital twins and other Industry 4.0 technologies.

Ontology mappings reflect unexplored areas in PVC recycling, which require attention for the sake of providing more insights that could help enhance the drive for a circular economy.

In addition, Big Data Analysis tools are rarely used in the research related to PVC recycling, which could have enhanced the viability and reliability of the results obtained from this research.

## 8. Current Challenges and Breakthroughs in PVC Recycling

### *8.1. Material Composition and Complexity*

Polyvinyl chloride (PVC) presents significant recycling challenges due to its complex composition. PVC primarily consists of carbon (55–57%), chlorine (~41%), and oxygen (2–4%), with the latter often arising from thermal oxidation during processing.

The material's high additive content, including plasticizers, stabilizers, and pigments, further complicates recycling processes. Notably, plasticizers such as bis(2-ethylhexyl) phthalate (DEHP), an endocrine disruptor, have faced regulatory bans due to environmental and health concerns [41].

The dynamic nature of PVC waste, derived from post-consumer, industrial, and construction sources, exacerbates recycling challenges [23].

Additionally, its integration into composite products like coated fabrics or natural fillers, such as rice husk, complicates separation and recycling due to the material incompatibility [8,90,91].

### 8.2. Technical Limitations in Current Methods

The recycling of PVC is constrained by the technical limitations of current methods. Mechanical recycling, the most common approach, often results in degraded mechanical properties due to repeated thermal processing, which reduces the melt strength and compromises the material integrity. This degradation is further exacerbated by the presence of mixed material streams, making recycled PVC unsuitable for high-performance applications [92].

Investments in advanced separation techniques for recovering PVC from composites and innovations in chemical recycling to convert PVC waste into valuable feedstock with a minimal environmental impact are critical [8,88].

It is necessary to explore the use of Big Data and artificial intelligence in PVC recycling to enhance existing technologies and improve process efficiency.

### 8.3. Economic Viability and Market Challenges

Despite its broad applications, PVC recycling faces challenges related to economic viability and market acceptance. A high energy consumption and inconsistent quality outputs make recycled PVC less attractive compared to virgin materials [23]. Contaminants, such as DEHP, complicate recycling processes, leading to increased operational costs and fluctuating raw material prices [41,47].

Mechanical recycling often results in diminished material properties, discouraging manufacturers from adopting recycled PVC for high-performance applications. For instance, recycled PVC's use in flooring products can compromise the mechanical integrity, creating doubts among manufacturers [8].

Additionally, consumer scepticism regarding the quality and efficacy of recycled PVC delays market adoption, affecting growth and sustainability goals [88].

## 9. Conclusions

This study underscores significant advancements in PVC recycling while recognizing the challenges associated with material quality retention, economic viability, and regulatory inconsistencies. By integrating advanced manufacturing technologies and circular economy strategies, PVC recycling can evolve into a sustainable, resource-efficient system. Future efforts should prioritize regulatory harmonization, investments in infrastructure, and the implementation of intelligent manufacturing solutions to drive sustainability in PVC recycling.

### 9.1. Summary of Key Findings

The findings of this study indicate that PVC recycling is still undergoing a gradual yet progressive development. They also show that global cooperation and continuous research and development are crucial to achieving sustainability and a circular economy. Encouraging innovative PVC recycling technology could make recycling a widely adopted global practice with reduced costs in the foreseeable future.

### 9.2. Policy and Practice Recommendations

The urgency of addressing the enormous PVC waste and its environmental impact necessitates the formulation or revision of policies and the engagement of governments, global leaders, manufacturers, and industry stakeholders to rigorously adopt environmentally sustainable practices that benefit health and the environment. It is recommended that a universal template be adopted globally for policy formulation and implementation, with some allowances for adjustments to accommodate unique situations in different regions.

Collective effort appears to be the critical factor underpinning the accomplishment of the circular economy goal.

### 9.3. Future Directions for Research and Development

Future research must focus on scaling cost-effective recycling solutions, optimizing material designs for repeated use, and integrating regulatory frameworks to standardize PVC recycling processes globally. Digital technologies, such as block-chains for supply-chain transparency and AI-driven quality control, offer promising pathways to enhance material traceability and efficiency. A future PVC recycling industry dominated by AI-assisted smart machines could make circular economy objectives feasible. The ongoing transition from traditional to innovative PVC recycling methods (such as digitalisation and integrated engineering) is gradually resolving the scalability and pollution problems associated with current recycling methods.

By aligning with circular economy principles, PVC recycling can transition from a waste-intensive model to a sustainable, resource-efficient system.

It is also essential to introduce fermentation bioreactors for microbial PVC degradation, pursue lifecycle digitalization by means of AI and ontologies to facilitate traceable sustainability [93], and use modular machines designed for distributed recycling [54]. This section completes the research objectives by synthesizing technological, regulatory, and economic insights to propose actionable future directions.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/machines13050362/s1.

**Author Contributions:** Conceptualization, A.C. and K.C.; methodology, A.C., K.C. and D.G.; software, A.C.; validation, A.C., K.C. and D.G.; formal analysis, A.C.; investigation, A.C.; resources, K.C.; data curation, A.C.; and K.C. writing original draft preparation, A.C., K.C. and D.G.; writing review and editing, K.C. and D.G.; visualization, A.C.; supervision, K.C. and D.G.; project administration, K.C.; funding acquisition, D.G. and K.C. All authors have read and agreed to the published version of the manuscript.

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## References

1. Evode, N.; Qamar, S.A.; Bilal, M.; Barceló, D.; Iqbal, H.M.N. Plastic waste and its management strategies for environmental sustainability. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100142. [CrossRef]
2. Hossain, U.; Ng, S.T.; Dong, Y.; Amor, B. Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong Kong. *Waste Manag.* **2021**, *131*, 412–422. [CrossRef] [PubMed]
3. Čolnik, M.; Kotnik, P.; Knez, Ž.; Škerget, M. Degradation of Polyvinyl Chloride (PVC) Waste with Supercritical Water. *Processes* **2022**, *10*, 1940. [CrossRef]
4. Karlsson, T.M.; Arneborg, L.; Broström, G.; Almroth, B.C.; Gipperth, L.; Hassellöv, M. The unaccountability case of plastic pellet pollution. *Mar. Pollut. Bull.* **2018**, *129*, 52–60. [CrossRef]
5. Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L. Plastic waste inputs from land into the ocean. *Science* **2015**, *347*, 768–771. [CrossRef]
6. Turner, A.; Filella, M. Polyvinyl chloride in consumer and environmental plastics, with a particular focus on metal-based additives. *Environ. Sci. Process. Impacts* **2021**, *23*, 1376–1384. [CrossRef]
7. Everard, M. Twenty years of the Polyvinyl Chloride Sustainability Challenges. *J. Vinyl Addit. Technol.* **2019**, *26*, 390–402. [CrossRef]
8. Mirowski, J.; Oliwa, R.; Oleksy, M.; Tomaszewska, J.; Ryszkowska, J.; Budzik, G. Poly(vinyl chloride) Composites with Raspberry Pomace Filler. *Polymers* **2021**, *13*, 1079. [CrossRef]
9. Li, H.; Aguirre-Villegas, H.A.; Allen, R.D.; Bai, X.; Benson, C.H.; Beckham, G.T.; Bradshaw, S.L.; Brown, J.L.; Brown, R.C.; Cecon, V.S.; et al. Expanding plastics recycling technologies: Chemical aspects, technology status and challenges. *Green Chem.* **2022**, *24*, 8899–9002. [CrossRef]

10. Santos, G.; Esmizadeh, E.; Riahinezhad, M. Recycling Construction, Renovation, and Demolition Plastic Waste: Review of the status quo, challenges and opportunities. *J. Polym. Environ.* **2023**, *32*, 479–509. [CrossRef]
11. Martínez-Narro, G.; Hassan, S.; Phan, A.N. Chemical recycling of plastic waste for sustainable polymer manufacturing—A critical review. *J. Environ. Chem. Eng.* **2024**, *12*, 112323. [CrossRef]
12. Pomponi, F.; Moncaster, A. Circular economy for the built environment: A research framework. *J. Clean. Prod.* **2016**, *143*, 710–718. [CrossRef]
13. Cheng, K.; Srai, J.S. Special issue on sustainable manufacturing and the key enabling technologies. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2012**, *226*, 1603. [CrossRef]
14. Tridech, S.; Cheng, K. Low Carbon Manufacturing: Characterisation, theoretical models and implementation. *Int. J. Manuf. Res.* **2011**, *6*, 110–121. [CrossRef]
15. Peng, Y.; Dai, L.; Dai, A.; Wu, Q.; Zou, R.; Liu, Y.; Ruan, R.; Wang, Y. Catalytic process toward green recycling of polyvinyl chloride: A study on thermodynamic, kinetic and pyrolysis characteristics. *J. Anal. Appl. Pyrolysis* **2022**, *168*, 105719. [CrossRef]
16. Sadat-Shojai, M.; Bakhshandeh, G.-R. Recycling of PVC wastes. *Polym. Degrad. Stab.* **2010**, *96*, 404–415. [CrossRef]
17. Lewandowski, K.; Skórczewska, K. A brief review of Poly (Vinyl chloride) (PVC) recycling. *Polymers* **2022**, *14*, 3035. [CrossRef]
18. Fagnani, D.E.; Tami, J.L.; Copley, G.; Clemons, M.N.; Getzler, Y.D.Y.L.; McNeil, A.J. 100th Anniversary of Macromolecular Science Viewpoint: Redefining Sustainable Polymers. *ACS Macro Lett.* **2020**, *10*, 41–53. [CrossRef]
19. Shih, H.-S. Policy analysis on recycling fund management for E-waste in Taiwan under uncertainty. *J. Clean. Prod.* **2016**, *143*, 345–355. [CrossRef]
20. Miliute-Plepiene, J.; Fråne, A.; Almasi, A.M. Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries. *Clean. Eng. Technol.* **2021**, *4*, 100246. [CrossRef]
21. Department for Environment, Food and Rural Affairs. Environmental Improvement Plan: Annual Progress Report 2023 to 2024. gov.uk. Available online: https://www.gov.uk/government/publications/environmental-improvement-plan-annual-progress-report-2023-to-2024/environmental-improvement-plan-annual-progress-report-2023-to-2024 (accessed on 2 April 2025).
22. Atasu, A.; Subramanian, R. Extended producer responsibility for E-Waste: Individual or collective producer responsibility? *Prod. Oper. Manag.* **2012**, *21*, 1042–1059. [CrossRef]
23. Ait-Touchente, Z.; Khellaf, M.; Raffin, G.; Lebaz, N.; Elaissari, A. Recent advances in polyvinyl chloride (PVC) recycling. *Polym. Adv. Technol.* **2023**, *35*, e6228. [CrossRef]
24. Elgarahy, A.M.; Priya, A.K.; Mostafa, H.Y.; Zaki, E.G.; Elsaeed, S.M.; Muruganandam, M.; Elwakeel, K.Z. Toward a circular economy: Investigating the effectiveness of different plastic waste management strategies: A comprehensive review. *J. Environ. Chem. Eng.* **2023**, *11*, 110993. [CrossRef]
25. Wang, J.; Wang, F.; Duan, H.; Li, Y.; Xu, J.; Huang, Y.; Liu, B.; Zhang, T. Polyvinyl Chloride-Derived carbon spheres for $CO_2$ adsorption. *ChemSusChem* **2020**, *13*, 6426–6432. [CrossRef]
26. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, 71. [CrossRef]
27. Mulder, K.; Knot, M. PVC plastic: A history of systems development and entrenchment. *Technol. Soc.* **2001**, *23*, 265–286. [CrossRef]
28. VinylPlus. The European PVC Industry's Commitment to Sustainable Development. 2018. Available online: https://www.pvc.at/wp-content/uploads/2020/09/VinylPlus-at-a-Glance-EN.pdf (accessed on 2 April 2025).
29. VinylPlus. *VinylPlus Progress Report 2020—VinylPlus*; VinylPlus: Brussels, Belgium, 2020; Available online: https://www.vinylplus.eu/resources/vinylplus-progress-report-2020 (accessed on 2 April 2025).
30. The Vinyl. PVC-Compounds for a Sustainable Future. 2023. Available online: https://cefic.org/responsible-care/2023-european-responsible-care-awards/pvc-compounds-for-a-sustainable-future (accessed on 1 April 2025).
31. Chen, Y.; Zhang, S.; Han, X.; Zhang, X.; Yi, M.; Yang, S.; Yu, D.; Liu, W. Catalytic dechlorination and charring reaction of polyvinyl chloride by CUAL layered double hydroxide. *Energy Fuels* **2018**, *32*, 2407–2413. [CrossRef]
32. Jha, R.K.; Neyhouse, B.J.; Young, M.S.; Fagnani, D.E.; McNeil, A.J. Revisiting poly (vinyl chloride) reactivity in the context of chemical recycling. *Chem. Sci.* **2024**, *15*, 5802–5813. [CrossRef]
33. Zhang, L.; Xu, Z. C, H, CL, and in element cycle in wastes: Vacuum pyrolysis of PVC plastic to recover indium in LCD panels and prepare carbon coating. *ACS Sustain. Chem. Eng.* **2017**, *5*, 8918–8929. [CrossRef]
34. Lu, L.; Li, W.; Cheng, Y.; Liu, M. Chemical recycling technologies for PVC waste and PVC-containing plastic waste: A review. *Waste Manag.* **2023**, *166*, 245–258. [CrossRef]
35. Wiesinger, H.; Bleuler, C.; Christen, V.; Favreau, P.; Hellweg, S.; Langer, M.; Pasquettaz, R.; Schönborn, A.; Wang, Z. Legacy and emerging plasticizers and stabilizers in PVC floorings and implications for recycling. *Environ. Sci. Technol.* **2024**, *58*, 1894–1907. [CrossRef] [PubMed]
36. Sherwood, J. Closed-Loop recycling of polymers using solvents. *Johns. Matthey Technol. Rev.* **2019**, *64*, 4–15. [CrossRef]

37. Boaretti, C.; Donadini, R.; Roso, M.; Lorenzetti, A.; Modesti, M. Transesterification of BiS (2-Ethylhexyl) phthalate for the recycling of flexible polyvinyl chloride scraps in the circular economy framework. *Ind. Eng. Chem. Res.* **2021**, *60*, 17750–17760. [CrossRef]
38. Normand, A.T.; Wu, Y.; Régnier, T.; Fleurat-Lessard, P.; Rousselin, Y.; Théron, B.; Gendre, P.L.; Carta, M. Poly (vinyl chloride) Dechlorination Catalyzed by Zirconium. *Chem. A Eur. J.* **2024**, *30*, e202304005. [CrossRef] [PubMed]
39. Luciani, V.; Serranti, S.; Bonifazi, G.; Di Maio, F.; Rem, P. Quality control in the recycling stream of PVC from window frames by hyperspectral imaging. In Proceedings of the SPIE Optics + Optoelectronics 2013, Prague, Czech Republic, 15–18 April 2013; Volume 8774, p. 87741N. [CrossRef]
40. Phengsaart, T.; Julapong, P.; Manositchaikul, C.; Srichonphaisarn, P.; Rawangphai, M.; Juntarasakul, O.; Aikawa, K.; Jeon, S.; Park, I.; Tabelin, C.B.; et al. Recent Studies and Technologies in the Separation of Polyvinyl chloride for Resources Recycling: A Systematic review. *Sustainability* **2023**, *15*, 13842. [CrossRef]
41. Jaidev, K.; Suresh, S.S.; Gohatre, O.K.; Biswal, M.; Mohanty, S.; Nayak, S.K. Development of recycled blends based on cables and wires with plastic cabinets: An effective solution for value addition of hazardous waste plastics. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2020**, *38*, 312–321. [CrossRef]
42. Kye, H.; Han, S.; Han, J.; Hong, S.; Lee, D.; Bae, J.W. Eco-friendly technologies for physical and chemical recycling of PVC-Related wasteful resources. *Eng. J.* **2016**, *20*, 19–27. [CrossRef]
43. Chang, H.; Abu-Zahra, N. One step forward to a sustainable green solution for extruded foam PVC building products. *J. Vinyl Addit. Technol.* **2011**, *17*, 17–20. [CrossRef]
44. Carroll, W.F. Vinyl recycling: An update. *J. Vinyl Technol.* **1991**, *13*, 96–100. [CrossRef]
45. Steenblik, R. *Shift the Subsidies Database Reveals $40 Billion in Fossil Fuel Funding over Last Four Years—Oil Change International*; Oil Change International: Washington, DC, USA, 2011. Available online: http://priceofoil.org/shift-the-subsidies (accessed on 2 April 2025).
46. Amthiou, H.; Arioua, M.; Benbarrad, T. Digital Twins in Industry 4.0: A Literature review. *ITM Web Conf.* **2023**, *52*, 01002. [CrossRef]
47. Brignon, J.-M. Costs and benefits of recycling PVC contaminated with the legacy hazardous plasticizer DEHP. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2021**, *39*, 1185–1192. [CrossRef] [PubMed]
48. Grigorescu, R.M.; Ghioca, P.; Iancu, L.; David, M.E.; Ion, R.; Nicolae, C.; Gabor, R.A.; Radu, E.R.; Ganciarov, M.; Spurcaciu, B.; et al. Influence of non-metallic fraction of printed circuit boards waste on recycled polyvinyl chloride from waste wires. *J. Appl. Polym. Sci.* **2021**, *139*, 51469. [CrossRef]
49. Horodytska, O.; Cabanes, A.; Fullana, A. Non-intentionally added substances (NIAS) in recycled plastics. *Chemosphere* **2020**, *251*, 126373. [CrossRef] [PubMed]
50. Schyns, Z.O.G.; Shaver, M.P. Mechanical Recycling of Packaging Plastics: A review. *Macromol. Rapid Commun.* **2020**, *42*, e2000415. [CrossRef]
51. Khangale, U.; Benedictus; Ozor, P.A.; Mbohwa, C. A Review of Recent Trends and Status of Plastics Recycling in Industries. Available online: https://www.tci-thaijo.org/index.php/easr/index (accessed on 17 April 2025).
52. Maris, J.; Bourdon, S.; Brossard, J.-M.; Cauret, L.; Fontaine, L.; Montembault, V. Mechanical recycling: Compatibilization of mixed thermoplastic wastes. *Polym. Degrad. Stab.* **2017**, *147*, 245–266. [CrossRef]
53. Zhou, L.; Miller, J.; Vezza, J.; Mayster, M.; Raffay, M.; Justice, Q.; Tamimi, Z.A.; Hansotte, G.; Sunkara, L.D.; Bernat, J. Additive Manufacturing: A Comprehensive review. *Sensors* **2024**, *24*, 2668. [CrossRef]
54. Picchioni, F. Supercritical carbon dioxide and polymers: An interplay of science and technology. *Polym. Int.* **2014**, *63*, 1394–1399. [CrossRef]
55. Arshad, H.; Sulaiman, S.A.; Hussain, Z.; Naz, Y.; Basrawi, F. Microwave assisted pyrolysis of plastic waste for production of fuels: A review. *MATEC Web Conf.* **2017**, *131*, 02005. [CrossRef]
56. Versteeg, F.A.; Bollen, D.A.W.M.; Picchioni, F. Recycling PVC with $scCO_2$: From Soft to Rigid PVC. *ACS Sustain. Chem. Eng.* **2024**, *12*, 15398–15408. [CrossRef]
57. Truc, N.T.T.; Lee, B.-K. Sustainable and Selective Separation of PVC and ABS from a WEEE Plastic Mixture Using Microwave and/or Mild-Heat Treatment with Froth Flotation. *Environ. Sci. Technol.* **2016**, *50*, 10580–10587. [CrossRef]
58. Jiang, H.; Liu, W.; Zhang, X.; Qiao, J. Chemical recycling of plastics by Microwave-Assisted High-Temperature pyrolysis. *Glob. Chall.* **2020**, *4*, 1900074. [CrossRef] [PubMed]
59. Bharadwaj, C.; Purbey, R.; Bora, D.; Chetia, P.; Duarah, R.; Dutta, K.; Sadiku, E.R.; Varaprasad, K.; Jayaramudu, J. A review on sustainable PET recycling: Strategies and trends. *Mater. Today Sustain.* **2024**, *27*, 100936. [CrossRef]
60. Zhang, W.; Killian, L.; Thevenon, A. Electrochemical recycling of polymeric materials. *Chem. Sci.* **2024**, *15*, 8606–8624. [CrossRef] [PubMed]
61. Aji, I.; Sapuan, S.; Zainudin, E.; Abdan, K. Kenaf Fibres as Reinforcement for Polymeric Composites: A review. *Int. J. Mech. Mater. Eng.* **2009**, *4*, 239–248.

62. Sharuddin, S.D.A.; Abnisa, F.; Daud, W.M.A.W.; Aroua, M.K. A review on pyrolysis of plastic wastes. *Energy Convers. Manag.* **2016**, *115*, 308–326. [CrossRef]
63. Wilczewski, S.; Skórczewska, K.; Tomaszewska, J.; Osial, M.; Dąbrowska, A.; Nikiforow, K.; Jenczyk, P.; Grzywacz, H. Graphene modification by curcuminoids as an effective method to improve the dispersion and stability of PVC/Graphene nanocomposites. *Molecules* **2023**, *28*, 3383. [CrossRef]
64. Miandad, R.; Rehan, M.; Barakat, M.A.; Aburiazaiza, A.S.; Khan, H.; Ismail, I.M.I.; Dhavamani, J.; Gardy, J.; Hassanpour, A.; Nizami, A.-S. Catalytic pyrolysis of plastic waste: Moving toward pyrolysis based biorefineries. *Front. Energy Res.* **2019**, *7*, 27. [CrossRef]
65. Masoumi, H.; Safavi, S.M.; Khani, Z. Identification and classification of plastic resins using near infrared reflectance spectroscopy. *Int. J. Mech. Mechatron. Eng.* **2012**, *6*, 5. Available online: https://publications.waset.org/11237/identification-and-classification-of-plastic-resins-using-near-infrared-reflectance-spectroscopy (accessed on 17 April 2025).
66. Feng, Q.; Wang, K.; Yang, S.; Guo, J.; Chen, J.; Wang, T.; Liu, L.; Chen, Y. Non-Thermal plasma technology for further purification of flue gas in the resource utilization process of waste Mercury Catalyst: A case study in Xinjiang, China. *Processes* **2024**, *12*, 691. [CrossRef]
67. Motunrayo, A.; Adegoke, J. Innovations in Recycling Technologies for the Circular Economy. *Researchgate* **2023**.
68. Integrated Waste Management. Google Books. Available online: https://books.google.com.gh/books?id=qwwCEQAAQBAJ (accessed on 17 April 2025).
69. Lopez, G.; Artetxe, M.; Amutio, M.; Alvarez, J.; Bilbao, J.; Olazar, M. Recent advances in the gasification of waste plastics. A critical overview. *Renew. Sustain. Energy Rev.* **2017**, *82*, 576–596. [CrossRef]
70. Cong, R.; Fujiyama, A.; Matsumoto, T. Optimal plastic recycling system and technology development could accelerate decarbonization: A case study from Japan. *Waste Manag.* **2024**, *175*, 110–120. [CrossRef] [PubMed]
71. Pourali, M. Application of Plasma Gasification Technology in Waste to Energy—Challenges and Opportunities. *IEEE Trans. Sustain. Energy* **2010**, *1*, 125–130. [CrossRef]
72. Onn, M.; Suhana, H.; Razali, A.; Jasni, Z.J.; Zairul, A.A.Z. Types of Automated Recycling Machines for plastic Waste Management in Promoting Sustainability: A Short review. *Chem. Eng. Trans.* **2024**, *113*, 55–60.
73. Cheon, J.; Son, J.; Ahn, Y. Economic and environmental factor-integrated optimal model for plastic-waste sorting. *J. Ind. Eng. Chem.* **2024**, *139*, 162–174. [CrossRef]
74. Javaid, M.; Haleem, A.; Suman, R. Digital Twin applications toward Industry 4.0: A Review. *Cogn. Robot.* **2023**, *3*, 71–92. [CrossRef]
75. Imaekhai, L. Design and fabrication of a plastic film granulating machine. *J. Adv. Sci. Eng.* **2018**, *1*, 47–54. [CrossRef]
76. Buckshumiyan, A.; Babu, S.S.; Prakash, M.; Arasu, G.A. Recycling of plastic wastage by die shredder machine. *Mater. Today Proc.* 2023, *in press*. ISSN 2214-7853. [CrossRef]
77. Zubair, Z.; Iqbal, M.U.; Shah, T. Polymeric Materials. In *Engineering Materials*; Springer Nature Switzerland: Cham, Switzerland, 2024. [CrossRef]
78. May, G.; Kiritsis, D. Zero defect manufacturing strategies and platform for smart factories of industry 4.0. In Proceedings of the International Conference on the Industry 4.0 Model for Advanced Manufacturing, Belgrade, Serbia, 3–6 June 2019; Lecture Notes in Mechanical Engineering. Springer: Berlin/Heidelberg, Germany, 2019; pp. 142–152. [CrossRef]
79. Pires, F.; Cachada, A.; Barbosa, J.; Moreira, A.P.; Leitao, P. Digital Twin in Industry 4.0: Technologies, applications and challenges. In Proceedings of the 2022 IEEE 20th International Conference on Industrial Informatics (INDIN), Perth, Australia, 25–28 July 2022. [CrossRef]
80. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2015**, *114*, 11–32. [CrossRef]
81. Akshata, P. Critical Assessment of Circular Economy Regarding Waste Reduction and Optimal Use of Resources. 2022. Available online: https://www.researchgate.net/publication/351283756 (accessed on 17 April 2025).
82. King, S.; Locock, K.E.S. A circular economy framework for plastics: A semi-systematic review. *J. Clean. Prod.* **2022**, *364*, 132503. [CrossRef]
83. Circular Economy Project. Ontology for Circular Economy Project. Developed Using Protégé (Version [Protégé-5.6.3]). Available online: https://zenodo.org/uploads/15292909#basic-information-section (accessed on 3 April 2025).
84. Burelo, M.; Hernández-Varela, J.D.; Medina, D.I.; Treviño-Quintanilla, C.D. Recent developments in bio-based polyethylene: Degradation studies, waste management and recycling. *Heliyon* **2023**, *9*, e21374. [CrossRef] [PubMed]
85. Burelo, M.; Martínez, A.; Hernández-Varela, J.D.; Stringer, T.; Ramírez-Melgarejo, M.; Yau, A.Y.; Luna-Bárcenas, G.; Treviño-Quintanilla, C.D. Recent developments in synthesis, properties, applications and recycling of Bio-Based elastomers. *Molecules* **2024**, *29*, 387. [CrossRef] [PubMed]

86. Bonciu, F. Is Circular Economy Compatible with Capitalism? Is Circular Economy Compatible with Capitalism? 2020. Available online: https://www.researchgate.net/publication/342765144_IS_CIRCULAR_ECONOMY_COMPATIBLE_WITH_CAPITALISM (accessed on 17 April 2025).
87. Bac, U. The role of environmental factors in the investment prioritization of facilities using recycled PVC. *Pol. J. Environ. Stud.* **2021**, *30*, 2981–2993. [CrossRef]
88. Skelly, P.W.; Chang, C.F.; Braslau, R. Degradation of polyvinyl chloride by sequential dehydrochlorination and olefin metathesis. *ChemPlusChem* **2023**, *88*, e202300184. [CrossRef]
89. Sheldon, R.A. Green carbon and the chemical industry of the future. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2024**, *382*, 20230259. [CrossRef]
90. Ramle, M.S.; Romli, A.Z.; Abidin, M.H. Tensile properties of aminosilane treated rice husk/recycled PVC composite. *Adv. Mater. Res.* **2013**, *812*, 151–156. [CrossRef]
91. Kassab, A.; Nabhani, D.A.; Mohanty, P.; Pannier, C.; Ayoub, G.Y. Advancing Plastic Recycling: Challenges and opportunities in the integration of 3D printing and distributed recycling for a circular economy. *Polymers* **2023**, *15*, 3881. [CrossRef]
92. Windels, S.; Diefenhardt, T.; Jain, N.N.J.; Marquez, C.C.M.; Bals, S.S.B.; Schlummer, M.; De Vos, D.E. Catalytic upcycling of PVC waste-derived phthalate esters into safe, hydrogenated plasticizers. *Green Chem.* **2021**, *24*, 754–766. [CrossRef]
93. Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and chemical recycling of solid plastic waste. *Waste Manag.* **2017**, *69*, 24–58. [CrossRef]