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REVIEW

Recycling Construction, Renovation, and Demolition Plastic Waste: Review of the Status Quo, Challenges and Opportunities

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Abstract

End-of-life treatment of construction, renovation, and demolition (CRD) plastic waste generated from day-to-day applications of plastics in the construction industry can negatively impact the environment if not handled properly. Addressing this issue is crucial considering the current unprecedented increasing rate of the use of plastics in the construction industry all over the world. Globally, the current option for managing CRD plastic waste is mainly landfill due to inadequate guidelines and standards, avoidance of risk, and lack of knowledge and experience in recycling CRD plastic waste. This trend counteracts the efforts towards a circular economy and crude oil independency. Therefore, developing commercially feasible end-of-use recycling technologies is indispensable to guarantee a sustainable future for the plastics employed in the construction sector. Despite the high theoretical recyclability of the plastics, recycling CRD plastic waste is economically unattractive since the material is contaminated and difficult to sort and separate. In addition, the cost of recycling is hardly recovered because of the material's low value.

This paper reviews the status quo, technologies, challenges, barriers, opportunities and recent initiatives on recycling CRD plastic waste. The paper identifies the framework and technology modifications required to overcome the current obstacles to implementing commercial-scale recycling. It emphasizes the importance of establishing an effective collection network, imposing price signals by authorities to impress landfilling of CRD plastic waste, and developing policies and regulations to enforce manufacturers to take end-of-life responsibilities by up-designing the product considering facilitated recycling. The paper concludes with a focus on investigating recent global state-of-art measures taken to tackle barriers against CRD plastic waste recycling. This study will assist the plastic construction sector with manufacturing, recycling, policymaking, benchmarking purposes, and implementation considering environmental and economic benefits.

Keywords CRD plastic waste · Recycling · Circular economy · Construction industry · Sustainable development

Current State of CRD Plastic Waste

Construction, renovation, and demolition (CRD) wastes are produced by building structures when built, restored (retrofitted/renovated), or demolished. They can also be interchangeably referred to as construction and demolition (C&D) wastes [1]. Globally, CRD waste is the most significant waste stream by volume [2]. In the residential sector, renovation is the highest contributor to waste production, followed by demolition and construction. In the case of non-residential, the highest contributor is demolition, followed by renovation and construction [3].

In Canada, a significant portion of the solid waste stream is comprised of CRD waste, with the construction industry responsible for producing 9 million tonnes of CRD waste every year [4, 5]. It is expected that CRD waste volume will continue to grow in the future because of the stricter regulations imposed on their sorting, treating, reusing, and recycling. The urbanization and growth of the construction industry in developing countries may also contribute to CRD waste volume growth [2].

CRD wastes are typically comprised of bulky, heavy, and non-biodegradable materials [2]. These wastes include concrete, wood, asphalt, and plastics[6]. All construction,

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demolition, and renovation activities generate different types of waste materials [6]. New construction generates cut-offs, scraps, and packaging, which are relatively uncontaminated and easily sorted into bins to be recycled. Demolition activities produce mixed wastes that are usually contaminated and may be difficult to sort. Wastes from renovation activities generate a cross between what construction and demolition activities produce [1]. In the United States, demolition activities produced the majority of CRD waste, whilst construction comprised less than 10%. The predominant waste generator were non-residential demolition projects followed by the renovation of residential structures [6].

About 95% of the global CRD waste can be reused or recycled [2, 7, 8]. Globally, metal is the most recycled material from CRD waste (57.7%), followed by wood (31.0%). Lastly, despite being highly recyclable, plastics only make up 5.1% of the global recycled CRD waste in 2020 [2]. Much of these wastes can be reused for several useful applications such as fuel, aggregate, and manufactured products [6].

Frost & Sullivan (2020) estimated that 30% of CRD wastes in Canada were diverted from landfills from 2010 to 2020 [2]. In 2010 alone, Canada's 653,255 tonnes of CRD waste was diverted from landfills [9]. Quebec diverted the most CRD waste in 2010 (211,000 tonnes), followed by British Columbia (198,018 tonnes) and Ontario (154,722 tonnes). Only 16% of the total CRD waste was reused or recycled, highlighting the massive economic loss and missed opportunity for Canada to transition into a circular economy of plastics [1].

The construction sector is one of the biggest sectors responsible for the growth of the polymer industry, accounting for 19.8% of all plastic consumption in Europe [11]. In Canada, the number is even larger, with construction responsible for 26% of plastic entering the market [4]. Figure 1 shows the consumption and disposal of plastics in different industries in Canada in 2016 [4]. The construction industry's share in plastics consumption and disposal was 26% and 5%, respectively.

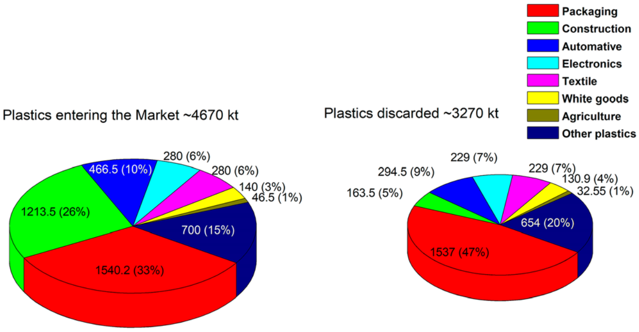

Fig. 1 Consumption (left) and disposal (right) of plastics broken down for each industry by weight (kt) and percentage (%) in Canada, 2016 [4]. EEE refers to the Electrical and Electronic Equipment industry; white goods refers to home appliances

Plastics have a wide range of unique properties that make them suitable for construction applications. They are lightweight, durable, anti-corrosive, fire resistant, and inexpensive, making them more attractive or use than other building materials [10, 12]. Polymers used in building applications can be categorized as the following:

- auxiliaries or support for other materials (e.g., adhesives).
- non-structural applications (e.g., floor and wall coverings).
- semi-structural and structural applications (e.g., polymer composites).

In the European continent, two-thirds of polyvinyl chloride (PVC) production is used for construction applications, including lining, flooring, window profiles, shutters, pipes, and cables [13]. The unique properties of PVC, such as its physical stability, resistance to cracking under stress, and versatility, make it a widely used polymer for building and construction (B&C) applications [14].

The other common polymer in construction is polystyrene (PS) which is used in two forms: expanded polystyrene (EPS) and extruded polystyrene (XPS). Their main application in the construction industry is insulation panels. Similarly, polyurethane (PU) is suited to insulation applications, because of its thermal insulation properties. High-density polyethylene (HDPE) and low-density polyethylene (LDPE) are also widely used in construction, mainly in pipes. Combined, HDPE and LDPE are responsible for 18% of plastic use in Europe [14]. HDPE is a chemically inert, rigid plastic resistant to cracking, while LDPE is characterized by its transparency, flexibility, and toughness [15]. Polypropylene (PP) is also used in pipes since it is rigid and resistant to stress cracking. It accounts for only a small fraction of European plastic use (2.5%).

In Canada, the use of plastics by the construction industry can be split into specific applications: plastic and foam building and construction materials is the largest user (16%), followed by paints and coating (4%), then profile shapes (4%) and lastly, wood products (3%) (Fig. 2) [4].

Rigid insulation is a notable construction material that makes use of PU, polyisocyanurate (PIR, polyiso, or ISO), and PS [1]. Carpet is another major application that uses polymeric, synthetic fibers such as nylon, polypropylene (olefin), acrylic, and polyester. Although natural materials, like wool and cotton, are used in the carpeting industry, synthetics are the dominant fiber used in North America's carpet industry.

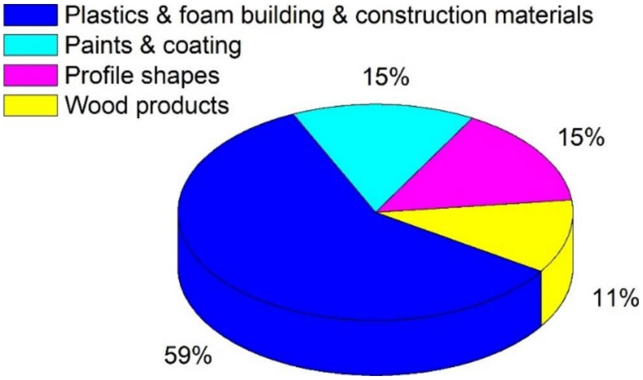

Fig. 2 Industries that use plastic products in Canada, further broken down into their applications [9]

Like Europe, PVC is widely used in Canada, particularly for B&C applications such as flooring, insulation, roofing, window profiles, and door profiles [4, 16]. Other plastics such as HDPE, polyethylene terephthalate (PET), LDPE, and PP are also commonly used in B&C applications. For example, LDPE and PET are utilized in construction packaging. Meanwhile, HDPE and PP are widely in piping [1].

At the global level, the composition of plastics within the CRD waste stream is unknown [17]. Data from Canada and Europe show that plastics comprise only a tiny fraction of CRD wastes by volume. However, the lightweight properties of plastics in CRD waste may lead to an underestimation of their volume in the waste stream [17, 18]. The lifetime of plastic products also plays an essential role in the minor contribution of plastics to CRD waste. Most plastics in construction applications remain “stocked” in buildings, meaning they have not reached the end of their service life [19]. The lifetime depends on the application; for example, wallpaper typically has a 5-year lifespan, while pipes can last for up to 80 years before being discarded. As the use of plastic products increase and their service lives end, this fraction may increase in the future.

Plastics generated and recovered from different CRD activities are activity-specific. For construction activities, about 80% of plastics produced are packaging that can be easily disposed of and remain uncontaminated. The waste generated is easier to sort since the wastes produced are known, compared to demolition activities [14]. In contrast, demolition sites generate little to no plastic packaging [20]. Plastics from demolition activities are at their end of life and were incorporated within the building structure. The goal of demolition activities is to demolish a building efficiently and quickly. Therefore, the plastic wastes are mixed with other debris, making them hard to separate. Meanwhile, renovation activities generate a combination of packaging and end-of-life plastics.

Table 1 Generated B&C plastic waste in Europe in 2018 [21]

Type of plastic	Total waste generation	
	By weight (kt)	*By percentage (%)*
Low-density polyethylene (LDPE)	90	5.1
High-density polyethylene (HDPE)	225	12.8
Polypropylene (PP)	130	7.4
Polystyrene (PS)	30	1.7
Expanded Polystyrene (EPS)	140	8.0
Polyvinyl chloride (PVC)	910	51.7
Other	235	13.4
Total	**1760**	**100.0**

Few studies quantify and categorize the plastic compositions of the CRD waste stream. A study by Lahtela et al. (2019) determined the polymer composition of manually and mechanically sorted CRD waste in Finland by using near-infrared spectroscopy spectra[17]. PP had the most significant fraction in the manually and mechanically sorted waste stream after removing the acrylonitrile butadiene styrene (ABS) outlier in the manually sorted waste stream. This comes as no surprise since PP is the most used polymer in Europe. PVC was also a significant polymer present in the waste sample. Notably, PVC was the most discarded plastic (51.3%) and 2.5 million tonnes of PVC waste was generated in Europe in 2013 for the B&C sector[13]. Other plastics found in Lahtela et. al.’s (2019) study were PE, which is typically used for plastic films and consumer products such as containers; polyamide (PA); PET; polymethyl methacrylate (PMMA); polycarbonate (PC); and PS. The study stressed the importance of avoiding dark plastics in the plastic industry, as there is no technology yet to separate different dark-coloured polymers from one another. Table 1 shows Europe’s B&C plastic waste generation [21].

Another study investigated the polymer fractions present in CRD waste in a landfill in Sao Paulo, Brazil [22]. The study found that PVC was the most significant plastic fraction in the rigid plastics category (32.7%), since they were used in many applications, most of them construction applications. Other rigid plastics also found were PET (7.2%), HDPE (18.3%), LDPE (0.1%), PP (5.3%), and PS (0.1%). The study also categorized plastic films, with polyethylene mixtures representing the largest fraction (23.2%). Other plastic films included LDPE (11.3%) and HDPE (1.6%). If only considering rigid plastics that have more important applications in the construction sector, PVC composed 51.3% of the total polymers in the investigated CRD waste stream. Construction is the second largest consumer of plastics in Canada. Most plastics in the construction sector end up being disposed(89%), with the consumption of plastics rising faster than its disposal [16, 23]. Compared to the packaging and the electrical and electronic equipment industries, only a small portion of plastics from the construction sector is recycled (Fig. 3) [23]. The disposal of plastics from all

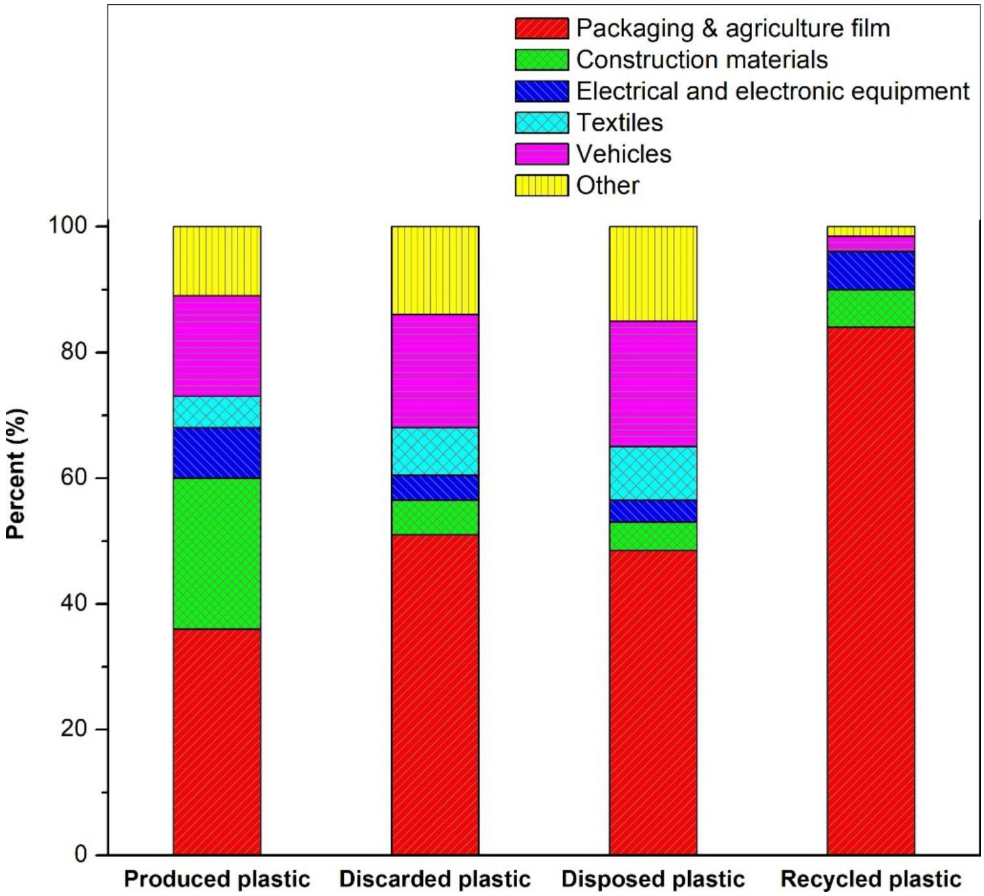

Fig. 3 Percentages of plastics at different life stages categorized by their application in Canada, 2018 [23]

sources accounted for a loss of 7.8 billion CAD in 2016, which is expected to increase to CAD 11.1 billion in 2030 under a business-as-usual scenario highlighting the missed massive economic opportunity of recycling plastic [10, 24].

Compared to Europe, most plastics originating from CRD waste end up in landfilling since Canada lacks established initiatives and frameworks to recycle them. Recycling plastic waste is constrained by the complex process of diverting to a landfill. Constraints for diversion include underdeveloped technologies for diversion, economic unviability and the diversion process itself being difficult. This is not made easier by the construction sector's low collection, sorting, and reprocessing rates since separation of most CRD wastes are not feasible technically or economically [4]. For example, processing facilities only allow for a 10% maximum contamination of CRD waste materials [1].

Studies investigating polymer composition in CRD waste in Canada are lacking. We may expect that it will reflect similar compositions as those seen in previous studies in Europe and South America. For example, a report by the Canadian Council of Ministers of the Environment (CCME) assessed the usage of several construction applications and their contribution to waste generation in Canada. Rigid insulation was more likely to produce plastic wastes from renovation and construction, while carpets generated large scraps from their replacement, or through demolition [1]. Polymers that were more likely to have rigid construction applications (e.g., HDPE, PVC, LDPE, PET, and PP) generated both small and large quantities of plastic waste produced from the construction, demolition, and renovation of structures.

Developing technologies and initiatives that take advantage of plastic wastes' high potential reusability and recyclability can impact their use in the construction industry, benefiting governments, businesses, and the environment. The construction industry may emerge as an important leader in developing the plastics recycling and recovery industry in Canada.

This paper aims to comprehensively review the current status of CRD plastic waste management, regulations, and techniques. It will start by reviewing the available recycling technologies along with their prospective opportunities. Next, the challenges and barriers around the low diversion rate of CRD plastic waste will be discussed. This will be followed by presenting the opportunities to tackle the barriers on recycling CRD plastic waste. Then, an overview of the recent developments in recycling CRD plastic waste will be provided which will focus on the four aspects which should be addressed to encourage the development of recycling technologies for CRD plastics. Lastly, the existing prospects and knowledge gaps in CRD plastic waste management will be highlighted.

Recycling of CRD Plastic Waste: Potential, Impact, Strategies, Initiatives and Cost

Markets for recycled CRD plastics are still developing or extremely limited because they encounter the following main barriers:

- High contamination with other materials;
- Difficulty in separating plastics from other materials;
- Low quality or low demand.

Virgin plastics are usually preferred over recycled plastics because of their known additive amount and high performance. It is also cost-competitive with recycled materials. In the following section, the potential and impact of recycling CRD plastic waste will be reviewed. Then, different recycling strategies will be summarized. We will finish this section by highlighting some of the global recycling initiatives and the cost of CRD plastic waste management.

Recycling Potential of CRD Plastic Wastes

Sorting, reprocessing, and recycling propensity is different for every plastic type (Fig. 4) [15]. The recyclability of plastics depends on the accessibility of recycling technologies and the economic viability of the recycling process [16]. There are two types of plastics: thermoplastics that can be heated and cooled to be molded into any shape and thermosets that are hardened or "cured" into a shape by forming a three-dimensional network.

Table 2 Different plastic types used in the construction industry [48]

Plastic type	Resin	Application
Thermoplastics	Polyethylene (PE)	Water pipes, vapor barrier, membranes, electric-cable insulation
	Polypropylene (PP)	Sewage pipes, water pipes, membranes
	Polystyrene (PS)	Electric-cable insulation, foamed plastic, lighting fixture
	Polyurethane (PUR)	Foamed plastics, grouting compounds
	Polyvinylchloride (PVC)	Plates, tubes, profiles, façade covers, roofing, wet wallpapers, foils, flooring, electric-cable insulation, window frames
Thermoset plastics	Phenol plastic (PF)	façade covers, interior walls, door handles, electric lining
	Unsaturated polyester (UP)	Bath- and shower boots, interior walls, façade covers, window frames, and gutter pipes.

Various types of commonly used plastics in the construction industry are tabulated in Table 2. Before today's regulation on plastic additives, most CRD plastics were treated as harmful waste with no value for recycling due to the high amounts of chemical additives such as heavy metals, softeners, and flame retarders [48].

Thermoset plastics are unrecyclable, but it was found that they can be reused in new resins as a filler [49]. Plastics separated by resin type have more value since they can be recycled into polymer-specific applications. For example, PVC is collected separately from other wastes so that they can be reused again in their old applications [49]. CRD plastics that are difficult to separate end up in mixed plastic waste, to be made into plastic lumber, highway barriers, and traffic cones. If the waste is still challenging to recycle, it is converted into chemicals and fuel. Thermoplastics with a high potential value of sorting, reprocessing, and recycling are shown in Fig. 4 [50]. PVC and vinyl siding can be efficiently sorted, highlighting its frequent use in recycled products [50].

To provide an example, the recycling potential of PVC cables and sheathings was quantified by Jakubowicz et al. (1999) [51]. They studied the aging effects of PVC cables and sheathings recovered from houses in Sweden that were built in 1964, 1971, and 1974. Through their experiments, they found that the mass loss of the plasticizer and the stabilizer led to the degradation of PVC, meaning oxidation did not play a role in its degradation. In testing the elongation at the break of the old, recovered cables and sheathings, the material did not show significant changes from the reference material. They also determined the old materials to have high residual stability, indicating that the material was still thermally stable. When subjecting the materials to accelerated aging, the tensile properties were not significantly impacted, with only a maximum change of 1%. Their findings highlighted that the performance and properties of old, used plastics such as PVC cables and sheathings are not significantly impacted, allowing them to be good candidates for reuse and mechanical recycling [51].

Environmental Impact of Recycling CRD PVC

In many applications, PVC is replacing traditional construction materials such as wood, concrete, and metals. PVC is used prevalently in the construction sector owing to its properties; thus, we give considerable focus on it as a case study to examine the impacts of CRD plastics on the environment. However, like any production process, it can have adverse environmental and health impacts. Primary or virgin PVC can emit greenhouse gases. PVC production also

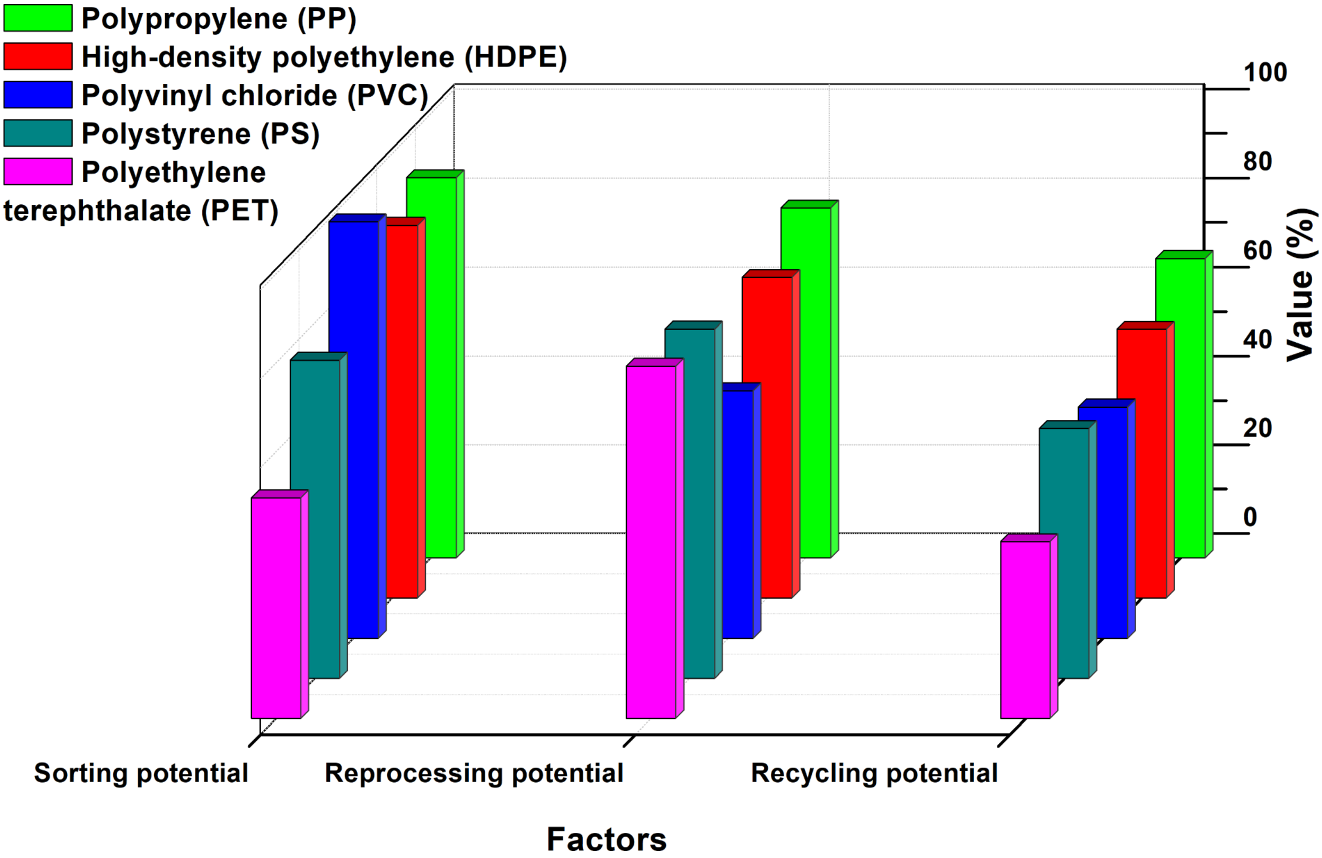

Fig. 4 Comparison of sorting, reprocessing, and recycling potential values of different plastic types [50]

uses heavy metals and phthalates, thus when it is incinerated, dioxins can be emitted. These concerns emphasize the need for an in-depth life cycle analysis (LCA) of PVC. While recycling PVC will reduce these environmental and health impacts, LCA of PVC accomplished by The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), Entec UK and Ecobalance UK, and Prognos AG revealed that the adverse environmental effects of using PVC in construction products are not substantially worse than any other alternatives [52].

Chen et al. (2019) found that environmental impacts were significantly reduced when mechanically recycled PVC was used instead of virgin PVC [35]. The environmental impact indicators that were reduced through mechanical recycling were the following: resource and energy consumption indicators; toxic effects indicators; and common environmental damage indicators [35]. Correspondingly, Ye et al. (2017) found that impacts on terrestrial ecotoxicity, human toxicity, marine ecotoxicity, and fossil depletion were significantly lower when recycled PVC was used [27]. For example, air pollutant concentrations were lower for recycled PVC (0.14 kg NOx/t and 0.04 kg SO_2/t) than for virgin PVC (0.43 kg NOx/t and 0.43 kg SO_2/t) (Ye et al., 2017). However, since data is variable within the country, these studies do not accurately represent the whole picture of China's recycled and virgin PVC production. Ye et al. (2017) also determined that climate impact can be reduced from 36.21 to 15.53% for each tonne of virgin PVC produced using clean energy [27]. This suggests that a shift to using alternative energy resources can lower the environmental impact of PVC production.

The environmental impact of recycled PVC, specifically from B&C applications, has also been the subject of LCAs. For instance, Stichnothe & Azapagic (2013) performed an LCA study on recycled PVC window profiles, which are responsible for about 8% of global PVC production [26]. Their analysis found that using post-consumer (or colored) PVC instead of virgin PVC resin can conserve 2 tonnes of CO_2 eq/t of PVC. For post-industrial PVC (or white-colored PVC), 1.8 tonnes could be conserved. On average, the use of abiotic resources and environmental impact for post-industrial recycled PVC was 85 times less than virgin PVC. Global warming potential (GWP), an indicator of the global warming impacts of different greenhouse gases, was also reduced 20 times (from 1910 to 100 kg CO_2 eq./t PVC). As for post-consumer recycled PVC, GWP impacts were reduced to an average of 34 times, and about 2056 of CO_2 eq,/t of PVC could be conserved as calculated from the

GWP (from 1910 kg to − 146 kg CO_2 eq./t PVC). In addition to a decrease in CO_2 emissions, a decreased impact on human toxicity and marine/terrestrial ecotoxicity was also found [27]. Some factors, however, were not included in the LCA study, like the presence of additives in the recycled PVC, which could affect the overall impact [26]. Hence, this comparison may not be completely accurate, highlighting the need for data for this particular factor to be incorporated. They also note that their data for recycled PVC and virgin PVC came from different sources, which can lead to different conclusions.

Another study by Seike et al. (2018) specifically looked at the environmental impact of PVC window sashes found in the municipalities of Hokkaido, Japan [53]. They calculated that about 233 kg CO_2/t was emitted when the sashes underwent a manual secondary separation during recycling. Secondary separation involved the process of discriminating between recyclable and non-recyclable PVC. When using machine separation, about 288 to 380 kg CO_2/t was emitted, about 55 kg CO_2/t higher than manual separation. This highlights the importance of treatment methods in impacting sash recycling emissions.

Both studies from Stichnothe & Azapagic (2013) and Seike et al. (2018) found that the farther a location is from a recycling plant, the higher the CO_2 emissions from recycling are [26, 53]. For example, the distance and truck payload (or the truck's capacity) had a major effect on the environmental impact of recycled PVC. Seike et al.'s (2018) LCA study determined that the city of Sapporo, where PVC sashes were collected and recycled, had the lowest CO_2 emissions when recycling [53]. On the other hand, the city of Nemuro, which was far from the recycling plant, saw a 92 kg CO_2/t increase compared to Sapporo.

Thus, collection and transport are integral to lowering the impacts of PVC production and recycling, which calls for the need to tackle logistical challenges such as collection and truck payload [26]. These studies highlight that recycling PVC can positively impact the environment and reduce one's carbon footprint, which may give companies and the government more incentive to invest in the recycling of CRD plastics. However, despite the environmental impact reduction of CRD plastic waste recycling, they are recycled infrequently due to several barriers that make establishing a recycling schematic difficult. These barriers will be highlighted later.

Recycling Strategies for CRD Plastic Waste

Recycled plastics, can be defined as the diverted waste originating from discarded plastic products, either finished or semi-finished, which can be utilized in the manufacture of a new or the same product [25]. There are two main methods by those plastics can be recycled: mechanical recycling and chemical (or feedstock) recycling. In both cases, the recycled material can be utilized to fabricate products for new or the same applications, thus reducing the consumption of new and raw materials. The chosen recycling process depends on the complexity of the waste stream and the degree of contamination [14].

Mechanical Recycling

Mechanical recycling is the primary recycling method used in recycling plants and also the main procedure within the construction industry. It involves physically breaking down the polymer product on the macro-scale (i.e., the polymer chain is not destroyed). Approximately 8% of plastic waste in Canada is processed using mechanical recycling [16]. This method processes the plastic waste through physical means, such as grinding or shredding [50]. The mechanical process produces an end product of plastic resins, pellets and flakes, sheets, repro and regrinds, and films [16].

Mechanical recycling can be subdivided into two categories: conventional and non-conventional. The conventional form of mechanical recycling typically involves the following general processes: grinding/shredding, decontamination, sorting of different materials (for example, removal of glass and metal), degranulation, extrusion, and then lastly, production of a recycled product [14]. The order of the steps can be altered and can be done nonconsecutively. The conventional method can only be efficient if large amounts of plastic waste are recovered and the material is of high quality. It is most suited to clean plastic wastes containing a single type of polymer, such as those used in window profiles and pipes, which are good candidates for conventional mechanical recycling [14]. Therefore, mixed and contaminated waste streams use the nonconventional mechanical recycling process. Nonconventional mechanical recycling involves chemical processing before or after conventional sorting to eliminate any waste other than the desired plastic. For example, chemical compatibilizers can be added to a mixed waste stream, to stabilize different polymer phases with differing thermal properties [54]. A notable nonconventional mechanical recycling technique called VinyLoop specifically recovers PVC from a complex or contaminated waste stream using a solvent to dissolve PVC selectively. Since the dissolved PVC is not converted into feedstock and retains its polymeric structure, the Vinyloop process is still considered mechanical recycling [13, 14].

Thermal reprocessing can be a step included in the mechanical recycling process. This process involves heating a thermoplastic at its melt temperature and manufacturing a new product from the melt product. This process is simple if only one type of thermoplastic is heated. However, if the plastics are mixed, as is the case for most CRD wastes, techniques such as compatibilizer addition, as mentioned before, can separate the different waste materials and polymer types [54].

Chemical or Feedstock Recycling

Chemical or feedstock recycling is a method where plastics are depolymerized, reverting them to their original building units, either as monomers, virgin resin, or energy [13, 25, 54]. Only about 1% of plastic waste in Canada is processed via chemical recycling [16]. Techniques to depolymerize the material include gasification, pyrolysis (thermal decomposition), hydrothermal depolymerization, dehalogenation, and chemolysis.

Gasification involves a thermal reaction where the amount of air, oxygen, or steam is controlled. This process yields syngas, a mixture of gases that include hydrogen, carbon monoxide, and small amounts of carbon dioxide. In the case of PVC, hydrochloric acid can be recovered to be reused again. For example, Sumitomo Metals uses iron- and steel-producing technologies that can recover HCl or $CaCl_2$ from mixed plastic and PVC-only wastes to produce high-energy syngas [13].

Dehalogenation is a chemical process that removes halogenated compounds from halogenated plastic materials, such as PVC. This is done to prevent damage to recycling equipment [55]. Feedstock can also be recovered in the dehalogenation process. A group at KU Leuven studied a dehydrochlorination process for PVC using non-volatile phosphonium ionic liquids heated to temperatures less energy-demanding than what was typically used in thermal dehydrochlorination (which can occur at temperatures over 400 °C). The process eliminated HCl under vacuum or gas, recovering dehydrochlorinated PVC polymers that can be used for possible recycling [56]. Another dehydrochlorination process investigated by AlzChem used an upstream extruder to degrade PVC at high temperatures. This technique removed chlorine from the plastic waste stream, recovering HCl [13]. Pyrolysis uses high temperatures in oxygen-starved conditions to decompose the polymer and recover carbon or heavy hydrocarbon residues [13]. Pyrolysis can be conducted in the absence of a catalyst (non-catalytic pyrolysis), in the presence of a catalyst (catalytic pyrolysis), and with the integration of thermochemical properties of plasma (plasma pyrolysis) [57]. Recently, hydrothermal depolymerization has employed sub- and supercritical water (T_c=647.3 K, P_c=22.1 MPa) to recycle plastic waste [58].

Chemolysis is a method that converts plastics into monomers using chemical or solvent treatments [55]. Specifically, the process where a solvent reacts with a compound is called solvolysis. Polymers undergo solvolysis to be depolymerized. Chemolysis only depolymerizes condensation polymers such as PET and polyurethane; it does not work for additive polymers like PE and PP [59]. Table 3 presents an overview of the different recycling techniques highlighting their key features that are used for plastics derived from CRD waste.

Global Recycling Initiatives for CRD Plastic Waste

Recycling of CRD plastic waste is managed by the stakeholders engaged. Linking the factors influencing CRD plastic waste management to each stakeholder clarifies their roles and responsibilities and helps them make better-informed decisions. The stakeholders can be classified as external and internal. External stakeholders are non-direct participants in construction projects and waste recycling including governments, the general public, and scientific experts. In contrast, the main internal stakeholders in the reverse-supply chain are manufacturers of plastics employed in the CRD industry, contractors, hauling operators of CRD waste, and waste recycling companies and facilities [60].

Effective interaction and communication between all stakeholders facilitate aligning their interests regarding the profitable recycling of CRD plastic waste and encourage manufacturers to modify plastic components and product design accordingly [61]. The product manufacturers of post-consumer plastic products directly manage many recycling programs. The manufacturers facilitate the recovery of relatively uncontaminated plastics by setting up guidelines and instructions so that the product is pure (not mixed) and relatively uncontaminated [62–64]. Contractors are hired to recover material from the construction or renovation worksite as per the instructions [62]. They deliver the material to be recycled to the following options:

- The product manufacturer’s facilities;
- A plastic recycling company approved for use in the program; or.
- A third-party facility participating in the program that may be a product distributor. The company delivers or ships plastic to the manufacturer once enough material has been accumulated to be beneficial, cost-wise [64].

Independent plastic recyclers also operate similarly to manufacturers’ voluntary programs. The barriers they face are similar in that acquiring a supply of CRD plastic wastes may be challenging, and they also need the establishment of reverse-supply chains. Therefore independent recyclers focus on recycling a specific application [65].

About 3,000 companies in Europe are part of the mechanical plastics recycling industry. Many facilities have readily

Table 3 Summarized recycling techniques for plastics from CRD waste [13, 55, 56, 59]

Recycling Method		Technique/Company and Country	Description
Mechanical recycling	**(Melt filtration and extrusion)**	Grinding, shredding, sorting, degranulation, melting to filter out impurities, extrusion, and manufacture of the recycled product [14].	
	Conventional sorting	R-Inversatech, Japan	High-speed beating rotor that separates PVC in tarpaulins.
		Hemawe/Caretta, Germany	Cutting PVC foil into strips, which are subsequently ground and sieved.
	Non-conventional modified sorting	AgPR, Germany	Cryogenic grinding and recycling of PVC flooring.
		Rubber Research Elastomerics, USA	PVC waste is mixed with tire scrap, which is recycled as a blend.
	Purification/Dissolution	Dissolving in a solvent, purification to separate the polymer from additives and contaminants, selective crystallization	
		VinyLoop, Italy	A selective solvent separates PVC from other materials by melting it. Evaporation of the solvent recovers PVC granules.
Chemical (or feedstock) recycling	Gasification	Production of synthesis gas by passing controlled oxygen and/or steam from feed material, chemical conversion of the gas into monomers	
		Sumitomo Metals, Japan	Recovery of HCl/$CaCl_2$ and syngas from PVC.
		Alzchem (pilot project), Germany	Removing chlorine from plastic wastes with PVC using an upstream extruder. HCl is recovered.
		KU Leuven, Belgium	Dehydrochlorination of PVC in non-volatile ionic liquids. Dehydrochlorinated PVC is recovered.
	Pyrolysis*	Non-catalytic Pyrolysis: Thermal decomposition in the absence of oxygen and catalyst Catalytic Pyrolysis: Thermal decomposition in the absence of oxygen but in the presence of a catalyst Plasma pyrolysis: Using thermo-mechanical properties of plasma to promote conventional pyrolysis	
	Chemolysis*	Breakdown plastic materials into monomers using a chemical agent	
	Hydrothermal depolymerization*	Break hydrocarbon bonds using water at elevated pressure and temperature	

* Chemolysis, hydrothermal recycling, and pyrolysis technologies are currently used only at demonstration facilities or still at the laboratory stage [57].

We couldn't find any company using the above for plastic waste from CRD.

available technologies that can shred, grind, wash, regenerate and/or compound plastic wastes. However, less than a hundred companies process 80% of what is mechanically recycled. Companies also tend to recycle only a specific plastic type from the waste stream [14]. Since more than 75% of PVC is used for industrial applications in Europe and is the most used polymer in the construction industry [66], this section will focus on recycling frameworks for PVC.

In 2020, 728,828 tonnes of this PVC were recycled [67]. Most of the PVC recycled were construction productions (Fig. 5), including window profiles and similar products (353 thousand tonnes) and flexible PVC and films used for roofing membranes. This was made possible by VinylPlus, Europe's 10-year voluntary commitment to develop sustainable methods of producing, using, and recycling PVC [13]. They established a goal of recycling 800,000 tonnes of PVC annually by 2020.

Recovinyl is an organization within the VinylPlus framework whose primary goal is to optimize and encourage PVC recycling in Europe [67]. They do this by monitoring the recycled PVC waste, connecting recyclers and converters to facilitate a circular economy of PVC, and monitoring

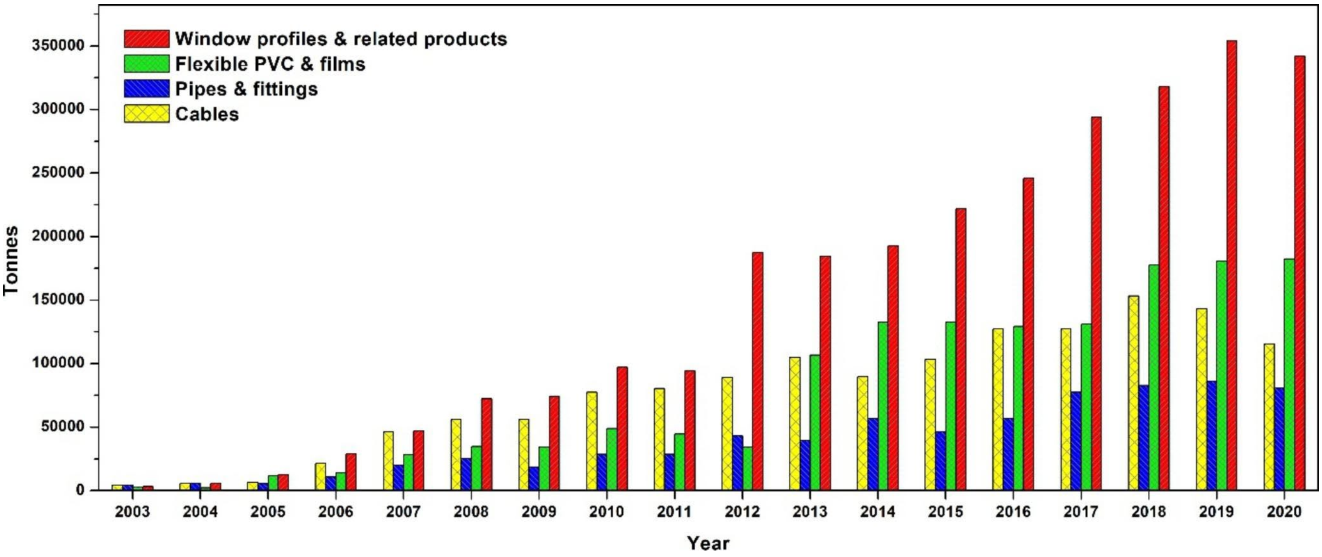

Fig. 5 Volume of PVC recycled in Europe within the VinylPlus framework from 2003 to 2020; categorized by application [67]

PVC quality and safety by tracing its path in the recycling process.

In Europe, most plastic wastes from building and construction sites can be readily managed and recycled, provided they are sorted first and are mostly uncontaminated [68]. Sorting is less complex when waste is produced from construction. Post-consumer products such as PVC frames and shutters, membranes, pipes, and packaging can all be placed in specific bags. Roofing products manufacturers may also have a take-back program. Demolition wastes are more challenging to sort and as a result specific recycling centers sort these types of waste.

A report on the use of PVC in Nordic countries (Denmark, Finland, Norway, and Sweden) examined the current collection and recycling systems they have in place [66]. Unlike Germany, few established systems were in place to recycle PVC in Scandinavia. For example, Germany recycled 214,340 tonnes of end-of-life PVC in 2020, most of which originated from windows and other profiles [67]. Meanwhile, the combined countries in the Nordic region recycled only 5,897 tonnes of PVC.

Despite having lower recycling rates than Germany, some Nordic countries (Sweden and Finland) have banned PVC wastes from being landfilled. In Norway, landfilling is more expensive than recycling PVC. In Denmark, only soft PVC can be landfilled [66]. In addition, a few Nordic countries have established collection systems for PVC in place. Denmark's national collection system for rigid PVC is called the WUPPI system (Wavin, Uponor, Plastmo, Primo, and Icopal).Around 1000 entities use the system, primarily private companies and some municipalities. About 2500 tonnes of this type of PVC are collected from the system annually [66, 69, 70]. For Finland, the Finnish Plastic Industries Federation monitors and collects PVC pipes. Sweden's Swedish Flooring Trade Association and Nordic Pipe Association collect 325 and 30 tonnes of used PVC material per year, respectively. Norway is also a member of RoofCollect, a thermoplastic roof membrane recycling system based in Germany that spans Europe [69].

However, few on-site recycling facilities exist in Nordic countries.As such, the PVC wastes from construction activities are mostly recycled abroad [66]. Germany is a significant player in recycling PVC wastes abroad and in their own country. The German industry network, AGPU, consists of 60 members in the PVC value chain. Among many responsibilities, they monitor PVC waste information such as generation and management [71, 72]. As a result, there are many established collection initiatives in Germany, most of them producers and recyclers. For example, there is Rohrrecycling in Westeregeln and Kunststoffrohnverband which takes back pipes and makes arrangements for their recycling; the Arbeitsgemeinschaft PVC-Bodenbelag Recycling (AgPR), which collects used PVC floor coverings; and the European Single Ply Waterproofing Association (ESWA), who collect and recycle post-consumers PVC waste from the building sector [73]. Germany mechanically recycles about 37% of PVC—the largest PVC recycling plant, Veka-Umwelttechnik GmbH (or Veka) recycles 50,000 tonnes annually [74]. A few recycling plants that can convert PVC-rich waste streams into feedstock also exist in Germany, such as DOW/BSL in Schkopau and Alzchem Trostberg GmbH in Hart [75].

In the Netherlands, a company called SRVKG (Stichting Recycling Vereniging Kunststof Gevelelementenindustrie) collects PVC window profiles to be recycled and reutilized again. The system is financed by disposal fees paid by waste owners and charges on imported PVC window frames. The Netherlands implements a 170 EUR/tonne charge because they do not have any domestic window manufacturers. As a result, recycling costs amount to 45 EUR/tonne for the waste generator, which is less expensive than disposal. Recycling starts with dropping PVC window frames at depositories, which are then mechanically recycled. The quality of the recyclate is high such that it can be reused again for new window profiles [76, 77].

The Netherlands also has a collection system for plastic pipes (made from PVC, PP, or PE) established by a company called BureauLeiding [78]. The costs associated with recycling plastic pipes are 560 EUR/tonne, with collection and logistics costing 120 EUR/tonne and treatment costs of 440 EUR/tonne. The waste owner is responsible for covering collection and transportation costs at transfer depots. Recycling has a deficit of 110 EUR per tonne of pipes collected through this system. The company seeks to cover all expenses without a deficit [14].

Belgium also has a collection system, called VAL-I-PAC, for plastic packaging waste produced by construction projects. Plastic packaging waste is collected in 400 L bags sold by the collection system at 1 EU/bag. The bags are transported, sorted, and mechanically recycled. The packaging wastes are estimated only to have a 5% impurity, allowing it to be recycled again as packaging, amongst other things. This system collected about 100 tonnes of plastic packaging in 2005 [14].

In Canada, several important CRD plastic manufacturers, recyclers, and waste haulers are currently in operation thatmanage specific CRD plastic applications. Recovered insulation boards are resold for a lower cost, and green builders may reuse them for insulation [1]. Reuse centers may accept whole insulation boards, but their applications may be limited to building envelope applications. Carpets also have several recycling facilities, such as carpet manufacturers who accept the return of their used products. For rigid plastics such as PVC and LDPE, the prices of scraps are variable. Plastics must be sorted into their respective polymer fractions to obtain the highest value. Mixed plastics either have no value or have minimal value ($20/tonne).

In Canada, the company Simplas collects and recycles PVC and PE pipe cutoffs and vinyl siding from CRD sites. However, the company's current operations are unknown as they have not updated their information as of 2012 [79].

Sika Canada Inc. is a manufacturer that has established roofing recycling programs in Toronto, Edmonton, and Vancouver [80]. With the purchase of a Sika roofing system product, they accept PVC roofing membranes at the end of their service life for recycling. For example, Sika roofing membrane from the Rogers Center in Toronto was recovered and recycled through Norwich Plastics [81]. Norwich Plastics recycles Sika's material in facilities in the U.S. and the last stages of processing in Canada. According to the company, they diverted 65 million pounds of PVC roofing from landfills since 2008 to be used again in the same product. Aside from roofing membranes, Norwich Plastics has also worked on the reclamation of rigid PVC pipe, profile, and siding from chicken coops in Neeb Haven Farms (New Hamburg, Ontario) and on reclaiming and recycling vinyl flooring with the Resilient Floor Covering Institute based in the U.S [81].

In Canada, several recycling programs are still under development. For example, the winners of ECCC's Plastic Innovation Challenge are developing the recycling of CRD waste into construction applications. One of these winners is Brantford, Ontario-based GreenMantra Technologies, who plans to convert PS insulation waste into new insulation [82]. MgO Systems is another winner from Calgary who aims to recycle and reuse old PVC from CRD and transform it into brand-new insulation.

Europe has many established recycling plants for PVC window and door profiles, but Canada and the United States lack these facilities. Since North America began using PVC profiles in the 1970s, Europe used these products much earlier [52, 83]. Window profiles have a service life of 30 to 50 years; thus, large amounts of material were found in the waste stream in Europe many years prior. Europe also has the advantage of the concentrated availability of materials because their populations are limited to certain geographic areas. This is the opposite of North America, where only small quantities of recyclable material are generated and collected since populations are geographically widespread [84].

Costs of CRD Plastic Waste Management Approaches

Diversion of CRD waste can be encouraged by implementing fees for waste producers and garbage collectors. A tipping fee is a cost applied to a specific amount of waste—usually done by weight—and is paid at the transfer depot, sorting facility, or landfill gate. Waste processing facilities can also have a tipping fee. Additional charges may be added or subtracted depending on the quality of the waste. For example, sorted waste may have a discounted cost, while mixed waste has an extra charge [1]. Facilities specializing in a certain material may have competitive fees to encourage targeted waste handling.

Table 4 compares the fees for different CRD plastic waste management techniques in some European countries. Germany can be considered the leader in recycling plastics from CRD waste since they recycled 40% of windows in 2004, which was relatively high compared to other countries in the EU [14]. The high landfill tariffs in Germany imposed on

Table 4 Summarized landfill, incineration, and recycling costs for some European countries

Country	Category	Fee per tonne	Reference
Germany	Landfill	€ 138	[14, 85] (in 2012)
	Landfilling PVC	€ 31 to 230	
	Incineration of PVC	€ 128 to 306	
	Recycling	Free (sorted and in large volumes)	
Belgium	Landfill	€ 85.96, including tax	[86] (in 2015)
	Recycling	€ 8,60 – 9,60	
Denmark	Landfill	€ 49, Landfill tax is € 64, Handling is € 1.8	[87] (in 2015)
	Recycling	€ 3 to 10*^{1}	
Netherlands	Landfilling CRD waste	€ 186 (including € 13 tax)	
	Landfilling PVC	€ 42–96 (including € 14 tax)	[88] (in 2015)

* According to savings when recycled instead of being landfilled

Table 5 Costs of landfilling vs. recycling in two case studies facilities [14, 89]

	Landfilling	Recycling
A pilot project in Brussels, Belgium	Road rental: 1.25€/m^2 per day Container rental: €54 per day Transport: €54 per container Landfilling: €80 per tonne Labor for sorting: NA	Road rental: 1.25€/m^2 per day Container rental: €54 per day Transport: €54 per container Recycling: €80 per tonne Labor for sorting: €30 per hour
Pearl River Delta, Guangzhou, China	On-site CRD transportation and collection: 50 yuan/tonne On-site sorting: NA Admission cost to landfill: 10 yuan/tonne Unit transport cost: 1.13 yuan/tonne/km	On-site CRD transportation and collection: 50 yuan/tonne On-site sorting: 20 yuan/tonne Admission cost to landfill: 0 yuan/tonne Unit transport cost: 1.13 yuan/tonne/km

CRD waste encouraged the sorting and recycling of plastics. In comparison, recycling is free, provided facilities accept large volumes of sorted CRD waste.

Pilot projects conducted in Europe highlighted that the main costs for recycling of CRD plastic waste were labor, transport, and road tax for containers in urban areas. The location and distance from the recycling facility are incredibly impactful; pressed plastics can reduce transport costs. Sorting costs, or labor, is also cost-intensive—however, an incentive is that plastics in mixed waste are more valuable when sorted. Similarly, wood or metal waste fetch a lower price when processed as mixed waste [14].

Comparing costs between recycling and landfilling depends on the labor costs of sorting and the locations of the recycling/sorting/landfilling facilities [14, 89]. Table 5 presents a comparative analysis of the costs associated with landfilling and recycling in two case study facilities in Belgium and China. As can be seen from the table, recycling would be less expensive if it wasn't for long sorting times. Meanwhile, landfilling does not require any physical labor. However, since sorting occurs as waste is generated from construction activities, this factor may not be as costly. This cost analysis also highlights the importance of recycling locations near the construction site for recycling costs to be equal to or even lower than landfilling. Road rental is also an essential factor in this example. The urban road to the building site allows only one truck container. Charges are based on the size of the container and how much it occupies the road [89].

If the mentioned criteria are not considered, landfilling plastics is more costly than recycling. The use of novel recycling technologies and the small amount of plastic waste recycled affects the costs of pilot recycling projects in Europe. These shortcomings show that there should be a focus on financing the aspects of sorting, container rental, and transport for recycling CRD plastics to be economically feasible.

Barriers to Recycling of CRD Plastic Waste

This section aims to determine the limitations of the establishment of a recycling process and implementation of commercial-scale recycling CRD plastic wastes. The intention is to identify the key factors that need to be addressed in design and operation to move toward profitable industrial-level recycling. Following is a summary of the barriers that arise across the globe in dealing with CRD plastic waste recycling.

Economic Limitations

Economic barriers denote the high recycling costs and high potential investment risk, making it less cost-competitive than landfill disposal. Limitations to the low competitive nature of recycling include:

- Low cost of landfilling, compared to recycling, separation, and sorting. In most cases, plastics are not separated during demolition activities since recovering and sorting them is costlier than landfilling them [90, 91].
- Low cost of incineration with energy recovery than recycling [92, 93].

- Virgin resin is the same price as recycled resin or cheaper andhe quality of virgin versus recycled resin is generally better. Thus, the plastic industry needs a higher value to incentivize more CRD plastic waste recycling [16, 94].
- Low demand for recycled material and products. Buyers of recovered material do not favor plastics with high contamination, which may result in low-quality products. These plastics are also not separated by resin type [95–98].
- Recyclers are not part of the bidding process in CRD projects, nor are they involved in planning them. General contractors may not put in the effort to recycle plastics even if they have specified they would do so since costs would increase [98].
- Recycling programs also have recycling incentives based on weight (such as LEED), which would discourage the recycling of light materials (i.e. plastics), and let workers focus on recycling heavier materials [99].

Construction and Demolition Sector Dynamics

Separation of plastics from other CRD wastes is a significant challenge in CRD activity sites. CRD sites are critical because preventing contamination and mixing of CRD plastics is most effective when separated at the source. Barriers to the construction and demolition sector dynamics are the following:

- Inadequate amount of space for bins that separate wastes [7, 100].
- Contractors are not willing to spend time separating wastes, as it may be costly.
- Insufficient worker training in recycling or separating plastics [98].

Logistical Challenges

Logistical challenges include returning post-consumer plastics to recyclers and product manufacturers to create a new recycled product. Barriers to logistics include:

- Lack of coordination among different CRD administration departments, including CRD site, government, and recycling facility [91, 101].
- Insufficient amount of plastics produced from CRD wastes. End-of-life plastics are generated in small amounts, which is not economically feasible [102–104].
- Lack of incentive for distributors to collect and store end-of-use plastics for recycling.
- Lack of accurate estimation of waste quantity, stable source of CRD waste for recycling, and distribution capacity [91].
- Lack of accommodation for a specific product in some recycling and manufacturing facilities. They may be restricted to one particular area that generates this plastic waste. For example, Canada lacks recycling facilities for the following plastics: EPS foam, PVC or ABS pipes or tarps, PP strapping, Tyvek building wrap, and PE wrap [1].
- Expensive or changing transportation costs. Facilities must be located close to be economically viable [1].
- Non-existent supply chains for CRD plastic products. A recycled product with no supply chain is not as cost-competitive as a virgin plastic product with an established supply chain [60, 105].
- Bulky plastic CRD materials that must be compressed or ground up before shipping to reduce costs in exporting. Balers may be needed on-site to compact plastic materials so they can be separated and ready for transport, unnecessarily taking up space [106].
- Restricted access of commercial businesses to materials recovery facilities (MRFs). Many construction activities generate plastic packaging wastes that are recyclable through the municipal system. MRFs also have fluctuating rules regarding whether plastic materials are accepted or not, making recycling more difficult and expensive [60, 107, 108].

To address the logistical challenges of recycling CRD plastic waste, including high transportation costs, an economical collection network scheme should be formed by governments in collaboration with industrial sectors. For example, plastic manufacturers can provide recycling services from CRD sites so that there is an off-taker for the recycling products. Moreover, such a scheme will provide a steady flow of recycling volume both from manufacturing scrap and end-of-use plastics in CRD waste. Considering logistic and economic aspects, one study on recycling suggested the recycling center should be located within 80 km of the site to avoid negating any environmental benefit [109].

Safety Limitations

Many plastics employed in the construction industry contain various additives necessary to provide them with the material properties needed for their intended final application. Many of these additives are toxic and harmful, and their existence in CRD plastic waste can limit their recyclability in both hygienic and property retention aspects [93].Legacy additives are substances that were legally allowed to be used in the production of a plastic product in the past. Now, they are no longer used under regulations imposed by the government, business, or industry [13]. Examples include lead and cadmium as stabilizers; low-molecular-weight phthalates were also used as plasticizers. Additives can prevent old, recycled products from being used in new plastic products. Incorporating non-legacy additives, such as plasticizers, fillers, and flame retardants in plastic products can also be a problem with recycling CRD plastics. These can serve as stabilizers or modifiers for the plastics product, however, they may impact the recyclability of plastic or aid in its degradation [16].

Acceptability Limitations

The recycling sector faces several issues in selling its products on the market, including the unintended negative perception of recycled products amongst the public and industry [60]. Despite the environmental benefit of recycling CRD plastic waste, studies show that recycled materials have been under-utilized due to their low acceptance within the industry, including the construction Sect. [110]. In some cases, the negative attitude toward recycled products is due to the lack of adequate knowledge and view of the recycled products' quality and market availability. A way of tackling the problem and avoiding potential negative assumptions is continuous prototyping and field trials during the design stage to confirm the acceptability [111].

Technical Limitations

These barriers refer to the American Society for Testing and Materials (ASTM), Canadian General Standards Board (CGSB), or industry standards that limit the amount of using recycled material in plastic products, as well as the challenges faced by recycling and sorting technologies. There is a severe mismatch in the present state of CRD waste recycling, as the current legislation lags behind the market demand.

Lack of Sorting, Separation, and Recycling Technologies

Plastics recovered from CRD activities are comingled with other wastes, such as wood, drywall/gypsum board, and asphalt shingles/roofing, among other things. The lack of a proper waste management plan, absence of regulations on on-site sorting, and lack of efficient technologies in sorting and recycling plastics that may damage currently-available equipment limits CRD plastic recycling [54, 91, 112]. In Canada, a maximum of 10% contamination is allowed for CRD waste materials to be processed by facilities [1]. Plastics may be highly contaminated with:

- Materials combined with the plastic to generate a product ; and/or.
- Material auxiliaries that secure plastics in place or create tight barriers (for example, adhesives and sealants).

MRFs also lack technologies for sorting plastics by resin type [113]. There are different types of plastics with unique molecular structures and properties, which means there are various melting points, rheology, and thermal stabilities [54]. The differences in properties can lead to the formation of discrete phases within a continuous phase, producing a plastic product with undesirable mechanical properties and low value [114]. As such, plastics almost always end up in landfill, as they are not fit to be recycled. Separating mixed CRD wastes is usually done by hand—which may be time-consuming—or by machinery. Thus, MRFs prioritize diverting materials with a higher value or a known diversion route. This results in the diversion of 75–90% of CRD wastes, yet plastics comprise the largest fraction that is not diverted [115]. Specific recycling technologies for a particular plastic or application may also be needed, restricting recycling to a specific geographic location. Sorting and recycling are easier to deal with when provided with application/plastic-specific facilities and allow easier manufacturing of recycled products [60, 113].

Disincentivizing the Recycling of PVC

PVC recycling is disincentivized because of the inclusion of PVC in "red lists", which categorizes it as a contaminant. Therefore, it is separated from other recyclable plastics and placed into the landfill category. This is a problem since as mentioned earlier, PVC is the most used polymer in construction applications. Contamination of PVC with other materials such as PET and also lower available volume of post-consumer PVC product (because of its long service-life) could be also contributing to low recycling rates of this CRD plastic [116].

Appearance and Performance of Recycled CRD Plastic Waste

The appearance of recycled plastics is usually undesirable. Since the material is not pure, the plastics are typically colored. It is also difficult to convert a dark-colored resin into a light-colored resin. For example, black vinyl flooring cannot be recycled back as a light-colored product. To be included in building and construction products, specific performance requirements and/or industry standards must be met by recycled plastic manufacturers. Usually, the amount of recycled material included in the new product depends on the application. However, impure plastic materials may result in a lower quality product and worse performance since plastic products are not designed to be recycled in the first place [16]. For example, recycling a mixture of used LDPE and HDPE may result in plastic that has holes. Also, some manufacturing processes for plastic products may not accommodate a variety of feedstock. Standards for plastic products such as ASTM, CGSB, or industry standards are also integral to assuring that the quality of the recycled material is adequate. For example, vapor barriers are subject to the CAN/CGSB-51.34-M86 in Canada, which does not allow any recycled content in new products [117].

Opportunities to Tackle Barriers to Recycling CRD Plastic Waste

Several essential stakeholders, including industry associations, certification bodies, private businesses in the CRD/waste hauler sectors, and governments, can tackle the barriers to CRD plastics recycling provided the following opportunities. The opportunities presented below target one or several of the barriers mentioned before that could lead to an increase in the volume of recycled or diverted CRD plastics:

- Increase landfilling charges by giving CRD plastic waste stream a specific waste classification that incurs higher fees or more radically making landfilling illegal and subject to fines [109]. Implementing a landfill tax or increasing landfill tipping fees will make recycling more cost-competitive [118].
- Implement a landfill ban for unsorted waste and “mono” landfills for recyclable materials to prevent untreated waste from entering backfill sites or legal dumping sites [119].
- Use waste bins to encourage on-site sorting in CRD projects. Sorting at the site of generation is more effective and will yield recovered plastic wastes of higher value [100]. However, building construction participants are reluctant to carry out on-site waste sorting due to limited site space, high labor costs, and time consumption [120].
- Track down where the CRD waste flows to hold waste-hauling companies accountable. Establishing a tracking system may help governments support incentive programs and guarantee that waste-hauling companies follow guidelines [121]. As for private companies, this also ensures that specifications or guidelines for green certification programs are being met [122].
- Conduct research and incentivize the diversion of highly contaminated or non-recyclable plastics for use in a variety of applications, such as waste-to-energy, asphalt/paving, cement kiln fuel, or as masonry in new construction infrastructure [123]. For example, more research is needed on the health effects of the fumes produced by PVC when it is burnt or used in asphalt [124].
- Work with governments to develop the maturity level of the legal framework and preferential policies and implement guidelines regarding [125]:
    - Requirements for the recycling of CRD plastic materials;
    - Bidding processes that allow recyclers to participate often result in minimal profit margins [64];
    - Auditing and tracking down recycled plastic materials ensures waste haulers and CRD companies recycle the material [126].
- Perform research on standards (CAN/CGB, ISO, and voluntary industry standards) for plastic construction products to find which applications allow recycled material in new products [125].
- Remove PVC from “red lists” and stop disincentivizing it to encourage recycling. PVC can be recycled multiple times and is a significant plastic used in construction projects, generating vast amounts of waste [127].
- Allow commercial businesses to use municipal MRFs. Packaging is the most generated plastic in construction projects, so these wastes can be easily diverted using the municipal system. MRFs should also consider recovering PVC plastics separately, which may encourage PVC recycling [128–130].
- Develop a network of major stakeholders through an online platform or government intervention [60, 131].

Recent Development on Recycling CRD Plastic Waste

We examine four distinct aspects within the literature to determine the recent development of CRD plastic waste management, including (a) decontamination of CRD waste; (b) separation and sorting of CRD plastic waste; (c) long-term performance assessment, condition monitoring and service-life performance evaluation of reused and recycled CRD plastic waste, and (d) the adequate percentage or quantity to replace raw material with reused/recycled CRD plastic waste.

Decontamination of CRD Plastic Waste

The extent of contamination in CRD plastic waste determines if the plastic material should be recycled or landfilled.

More often than not, plastics are too contaminated with other waste materials such as wood, glass, cement, and other aggregates, resulting in landfilling [132]. Therefore, decontamination is a necessary process that needs further investigation to maximize the recycling of CRD plastic waste.

The significant use of PVC in the construction industry as the most used polymer shows its high potential for recirculation in the supply chain [22, 64]. Thus, our search in academic and industrial literature specifically focused on the decontamination processes of PVC as a case study.

Different techniques are applied according to the contaminant to be removed. The decontamination process can be as simple as cleaning the plastic waste with water [22] and sometimes with water and detergent [28, 133]. The process removes any dirt or residue, such as adhesives and fiber. As pointed out by Hopewell et al. (2009), about 2 to 3 m^3 of water is used in cleaning 1 ton of plastics [116]. Other times, no water is used in the removal of residues, instead using friction, so-called "dry-cleaning". In a preliminary experiment by the Research Institutes of Sweden, the removal of acrylate-based adhesive from the back of PVC carpets was successfully achieved using detergent as well as using Envirostrip branded cleaning products [134]. The authors noted that mechanical washing was imperative for adhesive removal. As an example, company Tarkett has a glue removal process that consists of grinding the PVC carpets into pellets, then washing them in a basic solvent. From there the glue is removed using a filter, through which the PVC material can be recovered [134].

Some processes are more complex since they aim to remove additives such as plasticizers, flame retardants, legacy additives, etc., embedded within the plastic product. Eliminating these contaminants is integral to recovering a pure plastic compound that can be recycled as a new, high-quality product. For example, a process from hamos GmbH removed contamination such as seals, polyamides, and plasticized PVC from rigid PVC windows. The process involved grinding the window profiles, then using an electrostatic separator to separate rubber and contaminant fractions from the desired PVC material to obtain recycled PVC of 99.5% purity. After this step, a SEA optoelectric sorter removed any other rubber fractions and colored contaminants, yielding PVC regrind with a purity of 99.995% [135].

Solvents can also remove unwanted additives. Several organic solvents can precipitate out clean plastic compounds after being processed through azeotropic distillation, centrifugation, or filtration. Beneš et al. (2005) investigated the efficacy of four organic solvents (cyclohexane, dichloromethane, hexane, and tetrahydrofuran (THF)) that are typically used in recycling to extract the plasticizer dioctylphthalate (DOP) from PVC cable insulation [29]. Each separate solvent had a specific method: ultrasound treatment using hexane; dissolution by THF; and Soxhlet extraction in dichloromethane and cyclohexane. Ultrasound-enhanced hexane extraction efficiently separated DOP from the PVC matrix [29]. THF also extracted DOP and other compounds, making it viable for separating individual fractions from plastics. Dichloromethane and cyclohexane had low extraction efficiencies, making them unsuitable for plasticizer extraction.

The Vinyloop process by Solvay/SolVin is another dissolution process performed in a reactor, using methyl ethyl ketone (MEK) as a solvent [31]. This process sets itself apart from other dissolution processes because it has a precipitation step. The process begins by shredding composite PVC waste such as cabling, tarpaulins, and floor coverings, which are then dissolved in the solvent. Any non-PVC materials, such as copper from cables and glass fibers from floorings, are removed by centrifugation and sieving. PVC is precipitated from the solvent using steam (or water) and dried using centrifugation and a fluid bed. Any additional additives can be included during the process to customize the material for any desired applications. The recycled resin produced from the Vinyloop process is versatile and can be used for calendering, extruding, injection molding, and sintering to produce new recycled products. However, the VinyLoop plant in Ferrera, Italy, shut down in 2018 in light of the recent EU legislation on hazardous phthalate plasticizers present in recycled PVC material, which are costly to separate [136]. This shutdown highlights the need for developing a cost-effective solution and financial support for decontaminating PVC wastes.

Removal of legacy additives (lead stabilizer) from virgin PVC cable insulation cannot be achieved using the Vinyloop process. The Vinyloop technique is more appropriate for removing larger contaminants such as rubber, glass, and soil. However, Tsunekawa et al. (2011) found that by dissolving PVC cables in MEK and water, followed by high acceleration centrifugation with the addition of flocculants (polyethylene glycol and sodium lauryl sulfate), lead concentrations from recovered PVC decreased to below 1000 ppm. This number is the maximum limit for lead content as per the Restriction of Hazardous Substances (RoHS) in electric and electronic equipment [30].

Another method used to separate PVC from polyester in PVC-coated fabrics from construction applications, was investigated by Adanur et al. (2016) [32]. Absorption of the MEK solvent by the fabric through agitation separated the PVC and polyester components, so-called "swelling". Both polyester and PVC scraps were washed with water and dried in an oven. They found a loss of plasticizer from the PVC during the swelling process, which may degrade the performance of the recovered plastic. The authors suggested that the recovered PVC could be mixed with virgin PVC resin, yielding a product that can still have an adequate performance in the desired fabric product.

Instead of using organic solvents, Osada & Yana (2010) introduced diluted NaOH aqueous solution to extract DOP from a flexible PVC tube, typically used as a cable coating [137]. The authors achieved a complete extraction of DOP at a high temperature of 150 °C for 30 min using microwave heating. In this case, DOP was hydrolyzed and recovered as a phthalic acid and isooctanol. They achieved a separate dechlorination step when increasing the microwave temperature to 235 °C. Using external heat such as an electric heater resulted in the removal of plasticizers and chlorides simultaneously, necessitating an extra step where the plasticizer and chlorides are separated.

An alternative method by Tsunekawa et al. (2011) used a solid surface adsorption method to remove legacy additives (lead stabilizer) from virgin PVC cable insulation [30]. A strong acid cation exchange resin was used as an adsorbent and mixed with a chloride solution—after rinsing with water; the MEK solvent was added to the resin to dissolve PVC at high temperatures. This PVC solution was centrifuged, precipitating any calcium and lead stabilizers. The lead was removed by combining the PVC solution with the ion exchange resin; then it was mixed, sieved, and dried. Inductively coupled plasma analysis was used to determine the lead concentration in the PVC sample. The authors found that the different chloride solutions used in rinsing ion exchange resin recovered varying concentrations of lead [30]. Chloride solutions with high conductivity decreased electric repulsion forces, giving low lead concentrations. As such, the lead removal process was most effective when the chloride solution possessed high conductivity.

Melt filtration can also remove smaller contaminants to refine the purity of PVC waste. Melt filtration is a technology that separates components that do not melt (i.e. metals, papers, fibers, other polymers) under the processing conditions of that specific polymer by placing a screen before an extrusion die. Boo et al. (1992) tested several parameters that affect the melt filtration process of PVC (sourced from wiring, cable and similar applications), such as contaminant level, screen pack configuration, screw speed, and temperature [33]. They first performed preliminary decontamination and separation of rigid and flexible PVC using X-ray fluorescence spectroscopy and then density separation.

The melt filtration method further refines the purity of the PVC material; however, when there is more contamination, the recovered re-extruded product is of low quality [33]. This was because the screen area's efficacy increased as the impurity level decreased. The study pointed out that finer screens may be more suitable for filtering rubber particle contaminants. Temperature can also decrease the polymer's viscosity, thus lowering the pressure build-up behind the screen. Therefore, a high processing temperature is recommended, but not so much that it degrades the polymer.

The study estimated that rigid and flexible PVC waste can be melt filtrated provided that any impurities in the initial polymer material were only a few tenths of a percent. They also found that a continuous screen changer is most suitable for the decontamination PVC. All in all, melt filtration and compounding can be effective purity refining steps in recycling PVC [33].

A study by Kelly et al. (2005) examined other methods of decontamination and how they affected the properties of pre-consumer and post-consumer recycled unplasticized PVC window profiles [138]. The different decontamination techniques they compared included the removal of ferrous metals from pre-consumer PVC; removal of larger contaminants from gpost-consumer PVC; pulverization, melt filtration, and then pelletization of post-consumer PVC; and lastly, the Vinyloop dissolution of post-consumer PVC. The recyclates recovered from all decontamination procedures were processed using a single screw extruder.

The properties of PVC were affected under different decontamination procedures. The dissolution recyclate had the lowest viscosity, whilst the pre-consumer PVC had the highest [138]. Extrusion process variation was also affected. Recyclates with no contaminant removal had the most variation in processing, showing the significant effect contamination had on the material processability. To add, surface defects were most common in post-consumer recycled material, compared to virgin and pre-consumer material. The authors determined that mechanical and impact properties of the recycled material were either higher or comparable to the virgin reference material. Other tests such as thermal stability saw no significant changes for the recyclate.

The study showed that post-consumer recyclates can contain high levels of lead and cadmium. For example, the two post-consumer samples exceeded the maximum 100 mg/kg limit for cadmium. This is no problem for applications such as windows, pipes, and frames since there are no regulations for cadmium content in the EU. Still, it may pose problems in other countries where regulations for heavy metal content may be stricter [138].

The decontaminated recyclates obtained in Kelly et al.'s (2005) study were of high quality Even recycled samples with minimal decontamination, such as granulated post-consumer PVC, could be used in making a secondary plastic product. More complex decontamination processes, such as melt filtration and dissolution, yielded a high quality product but may not be economically viable if applied at the commercial scale. However, the PVC were obtained from different sources, therefore formulation differences may play a role in the high performance and quality of the recycled products [138].

Table 6 provides a comprehensive summary of decontamination procedures for CRD PVC waste, outlining the type of contamination removed, the specific decontamination procedure employed, and the original PVC application from which the waste originated. This compilation confirms that decontamination techniques for CRD plastic waste exist but are limited and there is a need for more research into this area since contaminants constitute a significant barrier to recycling CRD plastics, by degrading the recycled material quality and interfering with the processing equipment.

Table 6 Summary of decontamination procedures for CRD PVC waste

Contaminants Removed		Decontamination Procedure	PVC application	Reference
Removal of dirt and residue		Water and detergent	Rigid PVC pipes	[22]
			PVC jacket from electrical wires and cables; scrap vinyl siding	[28, 133]
		Envirostrip branded cleaning products.	Vinyl carpets	[134]
Removal of additives (e.g. plasticizers, flame retardants, legacy additives, etc.)	Seals, polyamides, and plasticized PVC	EKS electrostatic separator and a SEA optoelectric	PVC window profiles	[135]
	Plasticizer (dioctyl phthalate or DOP)	Ultrasound-enhanced hexane extraction, dissolution by THF, Soxhlet extraction in dichloromethane (small scale)	PVC cable insulation	[29]
	Rubber, glass, and soil	Vinyloop process (dissolution in MEK then precipitation using water)	Composite PVC waste (cabling, tarpaulins, and floor coverings)	[31]
	Polyester from PVC	Absorption of MEK through agitation, i.e. Swelling	PVC coated fabrics	[32]
	Lead	MEK and water, followed by high acceleration centrifugation with the addition of flocculants	PVC cable insulation	[30]
	Smaller contaminants (components that do not melt, i.e. metals, papers, fibers, and other polymers)	Melt filtration (placing a screen before an extrusion die)	PVC electrical wires and cables	[31]

Separation and Sorting of Plastics from CRD Wastes

Sorting is the process through which wastes are separated between valuable and non-valuable materials within the CRD waste stream. Typically, valuable materials can be recovered in a generally uncontaminated state, so they can be recycled or reused again. Plastics are particularly valuable since they can be recovered in relatively pristine conditions if handled appropriately. The methods of sorting plastics from a mixed CRD waste stream are worthwhile to look at since distinguishing plastics from other materials, such as wood, cement, gypsum, etc., is a crucial way to maximize its recycling potential.

Sorting is also a significant step in the mechanical process, either done manually or automatically [116]. Technologies used in sorting include Fourier-transform near-infrared (FT-NIR), X-ray detection, and Raman spectroscopy. Air elutriation, froth flotation, and “laser sorting”, which uses emission spectroscopy, can also be utilized to separate different polymer types.

Other techniques which improve the separation process include sink/float technology which utilizes a variety of mediums, such as water and brine, to separate materials from one another. For example, polyolefins can be separated from PVC, PET, and PS using sink/float separation. Electrostatic separation may also be used for plastic separation. Another method called froth flotation adds oils to a mixture of plastics to collect specific resins. Optical identification using spectroscopic techniques such as infrared radiation spectroscopy can also be used to separate plastics from one another by exploiting the different wavelengths that different polymers absorb or reflect. Using AI and deep learning allows the separation step in mechanical recycling to be done entirely automatically [13].

CRD wastes are included in a category called coarse wastes, since they are bulky [139]. Mechanical and manual technologies from the 1970s and 80s are still used to sort CRD wastes, despite new developments such as artificial intelligence (AI) based robotic systems typically used to sort small-scale wastes. Because of inefficient sorting techniques, huge amounts of recyclable material end up in landfill. Separation and sorting technologies can fall under one of three categories:

(i) Manual sorting, or sorting by hand, is usually implemented as a pre-sorting step to aid automated sorting technologies when dealing with complex waste streams [17, 34]. This type of sorting has high labor costs and is considered inefficient. Nevertheless, this method is best for distinguishing valuable materials from one another. For example, Lahtela et al. (2019) separated CRD plastics from other CRD waste categories by hand, then confirmed their polymer composition using a handheld Near Infrared (NIR) [17]. Manual sorting is often suggested as a pre-sorting step to make high-value materials easily distinguishable so that automated sorting technologies can easily discriminate materials within complex waste streams [34, 139].

(ii) Mechanical sorting is another common way to separate plastics from CRD wastes [13, 34, 140–142].The traditional mechanical sorting process begins with crushing coarse CRD materials, which are then passed through a vibrating screen to collect fine particles [143]. The remaining materials pass through an air-blowing machine, which separates a mixture of lighter matter (plastic, rubber, wood) from heavier materials. The heavier materials left behind are crushed yet again and made into recycled sand. Since many separated materials are mixed, the wastes are manually sorted by hand.

Air jigging is one mechanical sorting technique that separates materials by exploiting their different densities. By subjecting the particles of the materials to waves of air or water, the materials can form layers of increasing density. Ambrós et al.(2017) used air jigging to separate plastics, considered a light-density contaminant, from wood, gypsum, and paper in CRD waste. They found that plastics tend to be included with the desired light fraction and could block the dust collection system; specific technical alterations are needed to collect them separately as waste [140].

Serranti et al. (2012) also investigated another mechanical sorting process called magnetic density separation (MDS) [142]. MDS is a technique that utilizes a magnetic field and a dilute solution of water and ferrous oxide to separate polyolefins according to their density. A one-step separation is achieved using a gradient magnetic field and a magnetic liquid, in the same liquid medium. The technique is economically viable and environmentally friendly since it does not use organic solvents. Luciani et al. (2015) showed that a combination of innovative technologies, magnetic density separation (MDS) and hyperspectral imaging (HIS) is a promising approach for extracting high-quality PVC from window frame wastes [144]. The results verified the proper utilization of the Principle Component Analysis (PCA) and Partial Least Square Discriminant Analysis (PLS-DA) methodology to classify the PVC and rubber flakes coming from window frames. A high-speed rotating drum can also be used to improve the conventional mechanical recycling process and separate PVC and fibers from tarpaulins and wall coverings, as done by the company R-Inversatech [141]. The recovered PVC can be used for flooring and curing sheets. Another mechanical separation process by the company Hemawe/Caretta involves cutting PVC foil into strips, which are then ground and sieved to allow separation of the different materials. The resulting PVC can be used for pipe insulation, among other things [13].

Hyvärinen et al. (2020) investigated the mechanical method’s sorting efficiency. In their study, the materials were initially pre-sorted by hand, then mechanically sorted using a roller screen and an air separator. The material was fractioned into nine categories, one of them being the plastic category. Light plastic could be separated from heavier plastics (hard plastics) and other heavy non-plastic components such as wood and gypsum in the air separator. The authors noted that the heavier fraction should be further purified since the purity of the recovered hard plastics was only 50%, which is not of high value. Plastics and wood particles also have the potential to be separated using eddy current separation, as suggested by the authors, to further purify the recovered material [34]. Sensor-based separation was also suggested, provided it is economically feasible.

(iii) Automatic sorting uses cameras in combination with algorithms that can automatically identify an object and determine the material composition using spectral information. The automated sorting of CRD wastes is still being developed, especially sorting plastics from other CRD waste categories. The following specialized cameras can be used:

- Hyperspectral imaging (HSI) provides a high-accuracy identification of material composition, but geometrical dimensions of the material cannot be determined. Uses spectral information from NIR, VIS, SWIR, IR, or a combination of them [145].
- 3D cameras have a high accuracy of identifying material dimensions i.e., object identification, but cannot distinguish composition type [146].
- 2D cameras determines the geometrical outline and centroid of waste objects, like the 3D camera, but in a two-dimensional space [147] and can be used in combination with HSI.
- RGB cameras classifies objects by processing images into Red, Green, and Blue (RGB) and allotting a “fingerprint” onto the material. These cameras are restricted by the fragmentation of the waste, as well as the unique dimensions of CRD construction applications which makes classification difficult [139]. Objects can also cover each other within a waste stream, making

identification difficult. Images can either be captured in 2D or 3D space.

Sartipi et al. (2020) used HSI and 3D cameras equipped with RGB identification in their study and suggested that both types of cameras were needed for the identification of materials in complex waste streams such as CRD [146]. Their study used color coding to identify mixed aggregates from demolition waste. It could also determine the geometric dimensions of the particles, which can aid in the next steps of recycling the material. Seven different materials (including plastics) were distinguished using their specific colors with an accuracy of 87.5%.

HSI captures the NIR spectrum or the reflectivity of an object; from this, it can determine its makeup [143]. For example, Serranti et al. (2012) used HSI NIR to identify the purity of polyolefins that were separated from CRD waste with MDS [142]. Other times, HSI is used as a tool for automated sorting. When coupled with deep learning models, automated sorting CRD materials can yield high accuracy levels for classification. In most cases, analysis of objects happens offline, which is done by linear scanning and imaging; however, this method is not time efficient. Online classification is a quicker method in comparison but is limited by large data storage.

Xiao et al. (2019) developed an online classification system with HSI and a 2D camera [147]. They used extreme learning machine (ELM) and resemblance discriminant analysis (RDA) in the automation. The system could discriminate between foam, plastic, brick, concrete, and wood. They found that RDA had a higher efficiency and accuracy than ELM but was more suited to dealing with simple problems. Meanwhile, ELM could classify complex wastes but yielded low accuracy in classifying when it did have enough training data set. Training sets are required in deep learning models as they ensure quality control in the automated identification of waste materials. Minor alterations can also be made according to sensor response. For instance, De Groot et al. (1999) investigated how much a training set can be reduced without compromising the model's classification quality [148]. They classified between three waste categories (wood, plastic, and stone) using the linear discriminant analysis model, then tested two object selection methods: the Kennard-Stone algorithm and the statistical test procedure [148]. The authors found that the Kennard-Stone algorithm gave better training sets than those from the statistical test procedure, thus influencing the automated sorting of real CRD waste streams.

Xiao et al. (2019) also identified six types of CRD waste (wood, plastic, brick, concrete, rubber, and black brick) by exploring the use of a Pythagorean wavelet transform with HSI. The information obtained was more comprehensive and of higher quality than the original hyperspectral data. The authors also combined two algorithms: ELM and random forest (RF) algorithm method, to create the complementary troubleshooting (CT) method, which resulted in the identification of objects with 100% accuracy [145]. HSI was also used by Hollstein et al. (2017). Although plastic was considered a contaminant, it could still be identified accurately [149].

Ku et al. (2019) also developed a deep-learning robot equipped with HSI and 3D cameras that could separate CRD material. The authors used plastic bottles classified as CRD. The robot was composed of several parts: a hyperspectral camera, a laser beam, and a 3D camera to detect the objects; a conveyer belt to transport the CRD materials; and a gripper that grasps the materials after identification and sorts them according to the correct category [143]. The two types of deep learning for grasping were region-based convolutional neural network (RCNN) and auto-encoder (AE). Results found that without deep learning optimization, the robot was 70% successful when grasping objects that simulated messy conditions. When the deep learning model was added to the robot, the grasping rate improved to 90%.

Deep learning was also used by Davis et al. (2021) in combination with a GoPro camera. They used a deep CNN to discriminate hard and soft plastics along with six other typical CRD waste categories by utilizing images of on-site construction waste in bins [150]. This is different from other automated sorting technologies, which use conveyors to separate CRD waste, as it enables sorting on-site. The CNN method was 94% accurate in identifying a single waste category of CRD; for mixed CRD streams, it was 92% accurate in classifying the pre-determined fractions. Their work in the automated classification of CRD waste in bins is advantageous since managers can be informed of potential bin contamination and point to the possibility of CRD sorting on-site.

Automated sorting is a highly efficient process; however, advanced techniques such as the use of deep learning algorithms to sort and separate plastics from CRD waste have only been recently investigated. This could be because implementing the technologies (including specialized cameras) may not be economically viable [146]. Separation and sorting plastics is a worthwhile endeavor; however, more often than not, plastics are not classified in sorting and separating CRD materials as they are considered contaminants. Only a few studies have identified the plastics category explicitly in a CRD waste stream. Since plastics are a high-value material that can be put back into the plastic value chain, economic opportunities are lost due to the lack of automatic separation and sorting technologies. Different sorting and separation techniques currently used in CRD plastic waste management are summarized in Table 7.

Table 7 Summary of sorting and separation technologies for CRD plastic wastes

Sorting and Separation Technique	Procedure	CRD waste materials separated/identified	Reference
Manual (i.e. By hand)	Separation by hand, then the distinction of polymer fractions using a hand-held NIR tool	Plastics from other materials	[17]
	Separation by hand. Done as a pre-sorting step or after mechanical sorting.	Plastic, paper, and board, gypsum, concrete, porcelain, mineral wool, wood, metal, undefined and fines	[34]
Mechanical	Traditional mechanical process (crushing of CRD materials, passed through a vibrating screen, air blowing)	Plastic, paper, and board, gypsum, concrete and porcelain, mineral wool, wood, metal, undefined and fines; light and heavy (rigid) plastics from one another.	[34]
	Air jigging	Plastics*, concrete, brick, wood, gypsum, paper, etc. [*Plastic as a contaminant in this study, not as its separate fraction.]	[140]
	Magnetic density separation (MDS), i.e. Using a magnetic field and a solution to separate plastics	Mixed polyolefins (PP and PE)	[142]
	R-Inversatech process (high-speed drum)	PVC and fibers	[141]
	MDS combined with HSI	PVC from window frame waste	[144]
	Hemawe/Caretta (cutting, grinding, and sieving)	PVC foil from other miscellaneous materials	[13]
Automatic	HSI and 3D cameras (color-based detection)	Plastic, brick, ceramic, natural aggregate, glass, etc.	[146]
	HSI and 2D cameras with object classification algorithms (ELM and RDA)	Plastics, foam, brick, concrete, and wood	[147]
	HSI with the LDA model, using object classification algorithms (Kennard Stone algorithm or statistical test procedure)	Plastics, wood, and stone	[148]
	HIS (specifically NIR) combined with Pythagorean Wavelet Transform with object classification algorithms (EML and RF method)	Plastic, wood, brick, concrete, rubber, and black brick	[145]
	HSI with machine learning methods	Concrete, brick/roof tile, ceramics, stone, gypsum, floor/wall tile. Plastic is considered a contaminant.	[149]
	Gopro camera (2D camera) with an object classification algorithm (deep CNN)	Hard plastics, soft plastics, second fix timbers, shuttering/formwork timbers, shuttering formwork play and particle boards, bricks and concrete, cardboards and polystyrene	[150]

Below is a list of some of the companies with sorting and separation technologies for CRD plastic waste (Table 8).

Performance Assessment of CRD Plastics

The long-term performance assessment and service-life performance evaluation of reused and recycled CRD plastic waste is imperative to determine if recycling is a worthwhile venture to produce high-quality construction materials. Certain mechanical and thermal properties, as well as the durability of the CRD plastics, can be compromised after the recycling process. Mechanical properties usually measured to gauge the performance of plastics are tensile strength, elongation at break, modulus, and impact strength [36]. Examination of the impact of mechanical recycling processes on recycled CRD plastic properties compared to virgin plastic resin can reflect the physical and chemical aging of the plastic. In addition, the presence of additives in post-consumer CRD plastics must be examined since certain mechanical properties may be negatively or positively affected [38].

PVC is commonly recycled mechanically. During the recycling process, PVC may degrade, thus its mechanical and thermal properties, and subsequently, its performance may not be of sufficient standard. PVC can degrade quickly at high recycling temperatures, by processes such as dehydrochlorination, auto-oxidation, and mechano-chemical chain scission [36]. As a result, additives and stabilizers

Table 8 Companies that develop or provide sorting and separation technologies for CRD plastic waste

Company (Location)	Sorting/Separation Technology System
Machinex Industries (Plessisville, QC, Canada)	Offers two sorting systems: • Dry system: uses manual sorting or optical sensors. • Wet sorting system: makes use of sink-float tanks. Screens are utilized to sort CRD materials by size fraction. Plastics and PS comingled with other debris can be separated using this technology [151].
Waste Robotics Inc. (Trois-Rivières, QC, Canada)	Developed robots that specifically sort construction and deconstruction waste [152]. Rigid plastic, polyurethane, and other plastics can be distinguished using this technology. The'robot's components can be tailored according to what is needed to sort CRD waste. For the identification of material, hyperspectral, 3D, and 2D cameras are used to determine the composition, dimensions, and color of the waste materials respectively. The gripper, which manipulates the waste materials, can lift objects up to 25 kg.
ZenRobotics (Helsinki, Finland)	Developed the robot Heavy Picker, which can sort bulky and heavy CRD waste [153]. Different categories of waste can be sorted, such as plastics, wood, and metal. The robot can pick a maximum of 2300 objects per hour and handle wastes as heavy as 30 kg. RGB-, VIS- and hyperspectral cameras, as well as a 3D sensor system, are utilized to identify. Metals are also detected.
VanDyk Recycling Solutions, 2022 (Norwalk, Connecticut, USA)	Sorting systems supplier [154]. Utilizes air separation technology, specifically Walair Air Density Separation, is used to discriminate between heavy and light wastes. It also uses TOMRA sensor-based sorting by removing wood from the waste stream. Screens such as Lubo Trommels and/or StarScreens® separate different size fractions from one another. The Lubo bath separator separates buoyant materials and cleans heavy materials.
Bulk Handling Systems (Eugene, Oregon, USA)	Uses Nihot Single Drum Separator (SDS) to separate materials of different weights in CRD waste streams [155]. The SDS uses negative pressure technology and a splitter drum to sort the materials according to their density; in particular, plastics and film can be separated [156].
AMP Robotics (Colorado, USA)	Developed the sorting robot, AMP Cortex™, which is equipped with AMP AI technology [157]. The robot can sort, pick and manipulate waste materials, especially lighter materials such as plastics. It has a 99% accuracy and achieves 80 picks per minute.
EVK DI Kerschhaggl GmbH (Austria); OP Teknik (Sweden)	Designed the SELMA – OP Sorting System, an automatic sorting robot that can sort a variety of CRD materials using cameras, sensors, and AI technology [158]. Examples of plastics they sort include Styrofoam and polyethylene. 800 picks per hour can be achieved with 6 robotic systems.
Hamos GmbH, Germany	Constructed the hamos WRS recycling which can separate PVC from contaminants present in post-consumer PVC window profiles using a dry separation process [159]. The hamos WRS first removes the dust from granulated profile cutoffs. Next, the hamos EKS electrostatic separator segregates rubber and PVC. Lastly, clean PVC granules go through an optical sorter, where colored PVC is removed from the white PVC. Optical sorting uses equipment designed by Cimbria S.R.L., an optical sorting manufacturer (Cimbria, n.d.). In addition to sorting PVC by color, the SEA Vetro machine can remove the glass from PVC window profiles in sizes ranging from 1 to 50 mm; plastics can be segregated from the glass fraction. Full-colour RGB sensors are utilized to distinguish materials.

may be added to the material to reduce the likelihood of degradation.

Old plastic materials from CRD wastes are suitable for recycling since their mechanical properties remain similar to new, virgin plastic material. For example, Yarahmadi et al. (2003) subjected new and 20-year-old rigid PVC to high temperatures, which was then allowed to cool in a process called annealing [38]. The authors found that mechanical properties were retained even after 20 years of use for the rigid PVC. Tensile tests highlighted that impurities could severely decrease the elongation at the break of old rigid PVC material, showing the importance of the decontamination step in retaining acceptable mechanical properties. For example, the more contaminated white window profiles had elongation at the break that reduced from 137 to 82% after extrusion. In comparison, the brown profile (relatively uncontaminated) did not see much of a change (from 137 to 127% after extrusion). Heat treatment also decreased the elongation at the break of the old PVC profiles, below and above the glass transition temperature, T_g, which was attributed to physical aging and the destruction of the polymer chain orientation (crystallinity), respectively. However, when the materials were re-extruded, the original values for elongation at break were re-obtained due to a reversion of the original chain orientation of the material.

In that same vein, Yarahmadi et al., (2001) further tested the properties and durability of scrap rigid PVC profiles after several re-extrusion processes [37]. They did this by extruding new profiles one to five times, with no additional additives, then aging each extruded product at three temperatures (60, 70, and 75 °C) below PVC's glass transition temperature. They looked at the elongation at break, colour, and chemical properties of the various samples. They found that extrusion caused the yellowing of the material above the manufacturer's limit. An enhancement of the degree of gelation was observed (10%) from the original value after the second extrusion, which correlated with an increase in elongation at break (13%) between the first and third extrusions [37]. However, the material's rheology was shown to have degraded under shear after the fourth extrusion. Activation energies were shown to decrease after each extrusion process. From these measurements, the lifetime of the material decreased from 140 years after one extrusion to approximately 50 years after five extrusions. The study suggests that the PVC profiles have a long lifetime, even after passing through many extrusion processes, making them a good candidate for mechanical recycling.

Several studies have looked at the performance of recycled rigid PVC itself and found mechanical properties similar to virgin PVC material [22, 35, 36, 40]. For example, Ditta et al. (2004) investigated the number of times rigid PVC could be processed [36]. They examined samples of extruded lead-stabilized virgin PVC, Ca/Zn stabilized virgin PVC, and post-consumer rigid PVC windows. They found that the elongation at break for window profiles is similar to new, virgin stabilized PVC, even after 20 years of use. Tensile properties found little change between virgin PVC and old PVC window profiles if contamination, such as paint and glue, was kept to a minimum. They also found that the viscosity of the window profiles increased after several extrusion cycles, indicating the possible loss of additives during the extrusion process.

Prestes et al. (2012) also analyzed the performance of rigid PVC recovered from CRD waste [22]. They set a formulation of 84% recycled resin, 13.4% calcium carbonate, 1.9% stabilizer, and 0.7% titanium dioxide. This was similar in formulation to the virgin PVC, which used 84% virgin resin instead. In comparing the virgin and recycled samples for coarse and fine resins, they found no statistically significant difference in impact strength, tensile strength, and elongation at break. The study confirmed that these parameters were not affected in the recycling process, however, there was a significant difference in the modulus of elasticity in the recycled fine PVC resin. Since the rigid PVC pipes had already undergone processing in their first application, they underwent another round of compression molding in their second application, affecting their elasticity. In comparison, the virgin material had only undergone compression molding once. The authors concluded that chain breakage may have occurred during this second processing cycle which subjected the recovered PVC to the second round of mechanical stresses, melting, and possible contact with oxidizing agents. The cross-linking of chains during the dehydrochlorination reaction of PVC may have produced a more rigid structure. In another research Wenguang & La Mantia (1996) found that rigid PVC recycled from five-year-old pipes had increased elongation at break and impact strength values compared to virgin-grade PVC pipes. This may be attributed to additives that alter the impact properties of the pipes by playing a plasticizing role [40].

Recycled material can be treated to mimic the properties of virgin material. For instance, Prestes et al. (2015) indicated that recycled PVC material from pipes could retain similar properties to virgin material when surface-treated with plasma. By changing the surface of the polymeric material, PVC could be converted from hydrophilic into a hydrophobic surface, in turn changing many of its intrinsic properties. Fluorine atoms were present at the surface of the treated PVC, changing the chemical composition and thus increasing hydrophobicity to convert the hydrophilic surface into a hydrophobic one [160]. The surface electrical resistivity and roughness of the treated recycled PVC were similar to the untreated virgin PVC material. However, the abrasion strength of the recycled PVC slightly increased [160].

Several authors also examined the performance of recycled cables and wires, such as Roman & Zattera (2014), where they analyzed the mechanical and thermal properties of reprocessed PVC wires [161]. The study used a product standard from the Brazilian Association of Standards to compare the results. The results confirmed that despite the color change that occurred due to the degradation via the dehydrochlorination process, the material properties were within the standard requirement of up to five times reprocessing [161]. Similarly, Brebu et al. (2020) studied the characteristics of recycled 18-year-old PVC electrical cables (both insulation and jacket), which were compared to virgin PVC material with no additives and one with a similar formulation to the aged cables. The waste material was found to have higher T_g, signifying some PVC degradation (dehydrochlorination) occurred. The higher molecular weight of the recycled PVC compared to the virgin resin also implied incomplete dehydrochlorination. Thermal stability was the lowest for recycled PVC jackets, followed by recycled PVC cable insulation, virgin PVC, and PVC cable formulation. The study highlighted that many of the properties of PVC cable waste remained similar to the virgin material. However, the addition of stabilizers may be needed since the polymeric structure degraded, affecting the thermal stability [162]. The addition of additives in recycled PVC cable waste was also highlighted by Murata et al. (2002). They noted that the embrittlement property of cables with different ratios of recycled PVC material was worse than the virgin resin, emphasizing the need for an additional plasticizer [44]. The volume resistivity was affected negatively. However, the mechanical properties of recycled cable jackets were comparable to virgin resin and passed the performance standard. The appearance of the PVC jacket was affected, but this did not affect the properties.

Yarahmadi et al. (2003) examined changes to the properties of old post-consumer PVC flooring from buildings built in 1964, 1971, and 1974 [39]. They compared these materials to two types of new PVC flooring (heterogeneous and homogeneous). The homogeneous flooring was composed of approximately 85% recycled PVC waste. These samples were subjected to accelerated aging in three environments: flooring on glass (or the control), damp concrete, and flooring glued onto damp concrete. They found that the mechanical degradation of the two new floorings was minor. Measurement of the residual stability determined that the stabilizer was consumed with aging time and that moist concrete did not affect the stabilizer consumption. Low stabilizer consumption was also reflected in the old PVC flooring.

The study also examined the mass loss of plasticizers, leading to the degradation of the mechanical properties of the PVC material [39]. Plasticizer depletion was only available for the 1971 building and found no observable decrease over 30 years. In the homogeneous flooring, depletion was insignificant in all conditions, while the heterogeneous flooring saw a reduction of approximately 10% from the initial value, after 42 days at 80 °C. The authors observed that PVC flooring glued onto damp concrete could cause the decomposition of plasticizer because of high alkalinity; however, this depletion is minimal compared to when plasticizer is depleted through mass loss. Gluing the material produces decomposition products that may be detrimental to human health. This study showed that the addition of stabilizers and plasticizer is not needed in recycling new material. To include, gluing the product to moist concrete is not recommended as it makes disassembling the product more difficult and contaminates it.

The performance of plastic blends from a CRD waste stream has also been examined in the literature. Turku et al. (2017) analyzed recycled plastic blends from both CRD and household waste that were processed by injection molding. Manual separation of PP and PE from the construction waste was achieved in the analysis. They found that the tensile strength ranged from 16 to 25 MPa, while the modulus fell between 0.46 and 1.3GPa, which is considerably reduced compared to pure PP and PE plastics. This reduction in mechanical properties is attributed to the indiscrete phases of the blends and inadequate miscibility. This study emphasized the need for a separate system for mixed plastic wastes to recover pure plastic products with sufficient mechanical properties similar to pure plastic blends. Some degradation in the recycled blends was confirmed through FTIR analysis [163].

Recycling CRD plastic waste is a process that should be encouraged as old products that have undergone recycling can be reprocessed several times and still retain their properties. Contamination is highlighted in the literature as a big issue since it negatively impacts the mechanical properties of the recycled material, deeming it unfit for use in new recycled applications. Addition of additives may be needed to compensate for the additives loss during the old material's service life. In the case of plastic blends, the standards of the products may be insufficient; thus, plastic-plastic separation processes may aid in recovering relatively pure material to produce a high-quality recycled product.

Table 9 presents the properties have been assessed for performance evaluation of recycled CRD plastic waste. These properties may include mechanical strength, flexibility, impact resistance, thermal stability, chemical compatibility, and rheological behavior. Evaluating these properties is crucial in determining the potential uses of the recycled CRD plastic waste in various intended construction applications. The table highlights that only a handful of studies investigated the performance assessment of CRD plastic waste, but the few do look promising. In comparing recycled and virgin CRD plastics, we find that important properties are retained even after many years of use, provided they come from one plastic stream. More studies should be conducted to elucidate the performance of recycled CRD plastic products for use in the industry.

Recommended Recycled Plastic CRD Content

The recommended recycled content incorporated into new plastic products largely depends on the product application and what environment it will be subjected to. Most of the recommendations mentioned are specific to PVC products, such as flooring, profiles, membranes, and sidings. For example, Tarkett produces vinyl flooring with at least 40% recycled material, while their carpet tiles can contain as much as 80% recycled material. Window plastic frames made up of unplasticized PVC (PVC-U) can be recovered from demolition processes and are 100% recyclable [45]. The old PVC can be reprocessed a maximum of seven times without compromising its performance quality, but it can also be blended with virgin resin. For instance, Euro-Cell Recycling uses 50% recycled material in their products, while Belgium manufacturer/recycler Deceuninck,

Table 9 Summary of recycled CRD plastic waste performance and its applications

CRD Plastic Waste	Recycled CRD Plastic Application	Treatment	Performance/Properties Analyzed	Reference
Rigid PVC	*Window profiles*	Annealing	Elongation at break, differential thermal analysis (DSC)	[38]
		Repeated extrusion process (1–5 times), accelerated aging	Elongation and strength at break, color, dimensions, and weight, degree of gelation, residual stability, supercritical fluid extraction, chemical characteristics	[37]
		Repeated extrusion and injection molding	Rheology (shear viscosity), elongation, and strength at break	[36]
	PVC pipes	Mechanical recycling (calendaring)	Impact strength, tensile tests (tensile strength, elongation at break, modulus of elasticity)	[22]
		Compounding and extrusion	Dynamic thermal stability time (DTST), melt torque, tensile tests, impact strength, and dynamic mechanical properties	[40]
		Plasma treatment	Chemical composition, molecular structure, roughness, electrical resistivity, and abrasion resistance	[160]
Plasticized PVC	*Cables and wires*	Extrusion and thermal aging	Tensile strength, elongation at break	[161]
		Mechanical or cryogenic recycling	Gel permeation chromatography, elemental analysis, differential scanning calorimetry, T_g, static thermal stability, plasticizer absorption	[162]
		Extrusion	Volume resistivity, embrittlement, tensile strength (heated and room temperature), elongation at break (heated and room temperature)	[44]
		Natural aging, accelerated aging (heating)	Mechanical properties (tensile strength), stabilizer, plasticizer, and filler content (residual stability, supercritical fluid extraction, thermogravimetric analysis), bomb calorimetry (calorific heat values)	[39]
CRD plastic waste blend		Mechanically recycled (injection molding)	Tensile tests (tensile strength, tensile modulus, elongation at break), elemental analysis	[163]

incorporates as much as 100% recycled PVC [42, 164, 165]. Their process involves co-extrusion technologies that add a thin coat of virgin PVC to the core made of recycled PVC to improve the overall appearance.

For cabling, we did not find a specified recommended recycled content although Murata et al. (2002) tested different ratios of recycled PVC sheathing from cabling and wiring [44]. Incorporating different ratios of retrieved PVC jacketing material to unused PVC (100%:0; 2/3:1/3; 1/3:2/3; and 0:100%) found that mechanical properties were relatively unchanged and met the standard. However, volume resistivity and embrittlement were affected, as recycled content increased.

Plastic waste can be typically incorporated as aggregates in concrete blocks. This method is used when more complex recycling methods are unavailable [43]. Some studies use CRD plastic aggregate for use in concrete blocks. These studies usually only incorporate a small percentage of concrete since a higher plastic waste percentage can severely impact certain properties. For example, Mohammed et al. (2021) determined that a 30% (coarse) or 45% (fine) PVC aggregate ratio was the optimal content in concrete blocks [43]. Physical properties such as workability, absorption, and strength of the concrete were not affected, but elastic modulus was most affected when PVC aggregate content increased. Other studies tested CRD PVC aggregate content as high as 70% and as low as 2.5% [43, 166, 167].The rest of the recommended recycled content for other applications is summarized in the following table (Table 10).

Prospects and Knowledge Gaps

A beneficial outcome of the above review on CRD plastic waste is the identification of the knowledge gaps that need to be tackled to support the diversion of CRD plastics from landfills and recover higher value from waste to progress towards zero plastic waste and a circular economy. Below is the summary of identified knowledge gaps in this area:

Table 10 Summary of recommended recycled content in new plastic products

Product/Application	Recommended Recycled Content
PVC flooring	• Tarkett USA Inc. (manufacturer in the U.S.A.): o Vinyl flooring: 40% or more recycled material o Carpet tiles: as much as 80% recycled material [47].
PVC windows and door profiles	• Unspecified manufacturers: Up to 100% recycled PVC-U material and approximately 30% can also be included [45]. • Deceuninck (recycler in Belgium): As much as 100% recycled material except for a thin layer of virgin PVC to improve the appearance. This is achieved with co-extrusion technologies [42, 168]. • EuroCell Recycling (recycler/manufacturer in the U.K.): Use up to 50% recycled PVC [165].
Roofing and waterproofing membranes	• Up to 100% recycled material can be used in specific parts of the membrane. • Sika Sarnafil (manufacturer in the U.S.A.): Incorporates 10% of recycled content in single-ply roofing products [46].
PVC siding	No restriction on the amount of recycled content if the product meets performance standards. • Certaineed (manufacturer in the U.S.A) has CedarBoards D6 PVC siding product which contains a minimum of 60% post-consumer and post-industrial recycled material [167]
Pipes	European Product Standards (EN Product Standards) allow up to 100% recycled pipe material of select plastics (PVC-U and PP/PE) in new, reprocessed pipes [41]. • Prestes et al. (2012): containing 84% recycled PVC resin, 13.4% calcium carbonate, 1.9% stabilizer, and 0.7% titanium dioxide. Had mechanical properties similar to virgin resin except for the modulus of elasticity [22].
PVC wiring and cables	• Murata et al. (2002): Tested out different blending ratios of retrieved PVC jacketing material: unused PVC (100%:0; 2/3:1/3; 1/3:2/3; and 0:100%). Compared to virgin resin, mechanical properties were unchanged, the resistivity was reduced, and the embrittlement property was insufficient to meet the standard. The appearance of the material was granular but did not affect mechanical properties [44].
Bricks/asphalt	• Research is still needed. • Mohammed et al. (2019): 30% (coarse) or 45% (fine) PVC aggregate ratio was the optimal content in concrete blocks without affecting several mechanical properties [43]. • Incorporated 10% plastic with waste rubber, which enhanced elastic properties, and made it more resistant to rutting and cracking. • Lamba et al. (2022): The addition of 5% recycled PET improved compressive strength [169].

- Larger/commercial scale decontamination technologies are needed. The existing literature is limited to small-scale technologies.
- There is limited literature on sorting and separating various types of plastics (i.e., by polymer type). The existing technologies are primarily focused on separating plastics from more “valuable” materials, such as concrete, brick, wood, etc.
- Limited studies are available on CRD plastic wastes other than PVC (either rigid or plasticized), which seems to be the focus of the literature with respect to decontamination technologies, separating/sorting, as well as performance assessment.
- Information is lacking on decontamination technologies and performance assessment of severely contaminated CRD plastic waste (i.e., post-consumer), which are mainly mixed waste. Demolition activities mostly produce mixed plastic waste and finding the technology to decontaminate them for the target application is a challenge that needs to be addressed.
- There is lack of transparency regarding the costs of implementing decontamination, sorting/separation, and processing procedures in the literature. The total cost is still required to be calculated considering all the stages.
- There are limited studies on the percentage of recycled content. Most studies seem to focus on using CRD recycled waste as aggregates, instead of incorporating the recycled waste in the same B&C applications where they came from.
- Although a wide range of technologies are available, the possibility of their implementation on a commercial scale is still unknown due to the lack of transparency with logistical and economic challenges, which seem to be the biggest challenge to overcome.

Conclusion

The objective of this literature review was to examine the current state of recycling plastics from CRD wastes. We identified the existing recycling technologies, current challenges, barriers, opportunities as well as recent initiatives and knowledge gaps. Recycling CRD plastic waste can reduce environmental and human health impacts, as exemplified by several CRD waste impact studies. Notably, our findings determined that decontamination technologies for PVC CRD waste varied from simple washing to dissolution in a solvent. The ease of implementing decontamination methods was dependent on if the contaminant was incorporated within the product. Manual, mechanical, and automatic separation and sorting technologies existed for CRD plastics. Automatic separation and sorting is still a developing field but a promising venture that may be cost-effective. Performance assessments of CRD plastic wastes revealed that the quality of recycled CRD plastics may compete with virgin plastic material. In addition, it was determined that the suitable recycled CRD content in new products could range variably without compromising its performance. Our survey of the status quo emphasized the economic loss and missed opportunity to move toward a circular economy for plastics in the construction sector. Creating frameworks and initiatives to recycle CRD plastics has many economic and environmental benefits, which will encourage internal and external stakeholders in the recycling sector to promote the sustainable consumption of plastics.

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Declarations

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