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DOI
10.1016/j.scitotenv.2021.149892

Publication date
2022

Document Version
Final published version

Published in
Science of the Total Environment

Science of the Total Environment 803 (2022) 149892

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe

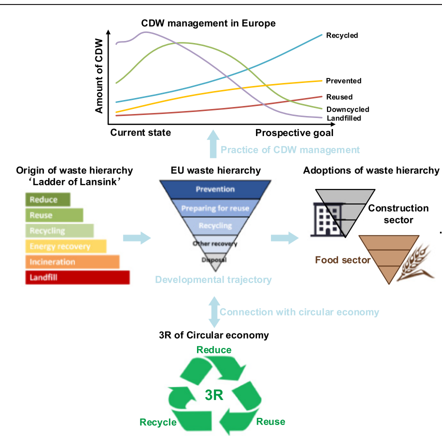
Chunbo Zhang [a], Mingming Hu [a,b,*], Francesco Di Maio [c], Benjamin Sprecher [d], Xining Yang [a], Arnold Tukker [a,e]

[a] Institute of Environmental Sciences, Leiden University, 2300 RA Leiden, Netherlands
[b] School of Construction Management and Real Estate, Chongqing University, Chongqing 40045, China
[c] Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN Delft, Netherlands
[d] Faculty of Industrial Design Engineering, Delft University of Technology, 2628 CE Delft, Netherlands
[e] Netherlands Organization for Applied Scientific Research TNO, 2595 DA Den Haag, Netherlands

HIGHLIGHTS

- Connections of the waste hierarchy and circular economy were compared.
- Developmental trajectory of waste hierarchy was identified.
- Lasted practice of construction and demolition waste management in Europe was presented.
- Novel technological routes for waste concrete management were introduced.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 July 2021
Received in revised form 11 August 2021
Accepted 21 August 2021
Available online 1 September 2021

Editor: Daniel CW Tsang

ABSTRACT

The construction sector is the biggest driver of resource consumption and waste generation in Europe. The European Union (EU) is making efforts to move from its traditional linear resource and waste management system in the construction sector to a level of high circularity. Based on the theory of circular economy, a new paradigm called waste hierarchy was introduced in the EU Waste Framework Directive. This work uses the framework of the waste hierarchy to analyze the practice of construction and demolition waste (CDW) management in Europe. We explore the evolution of the waste hierarchy in Europe and how it compares with the circular economy. Then, based on the framework, we analyze the performance of CDW management in each EU member state. Innovative treatment methods of CDW, focusing on waste concrete, is investigated. This brings insight into

Abbreviations: ADR, Advanced dry recovery; CDW, Construction and demolition waste; C2CA, EU Project C2CA: Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste; DFD, Design for dismantling; DFR, Design for recycling; D4D, Design for deconstruction; DOW, Designing out waste; EU, European Union; HAS, Heating air classification system; HISER, EU Project HISER: Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste; ICEBERG, EU Project ICEBERG: Innovative Circular Economy Based solutions demonstrating the Efficient recovery of valuable material Resources from the Generation of representative End-of-Life building materials; MS, Member state; PCE, Prefabricated concrete element; RQ, Research question; SCS, Smart crushing system; SI, Supporting Information; US, The United States; VEEP, EU Project VEEP: Cost-Effective Recycling of CDW in High Added Value Energy Efficient Prefabricated Concrete Components for Massive Retrofitting of our Built Environment; WFD, Waste Framework Directive; 3Rs, Reduce-reuse-recycle.

* Corresponding author at: Institute of Environmental Sciences, Leiden University, 2300 RA Leiden, Netherlands.
E-mail address: hu@cml.leidenuniv.nl (M. Hu).

https://doi.org/10.1016/j.scitotenv.2021.149892

Keywords:
Construction and demolition waste (CDW)
Waste hierarchy
Circular economy
Europe
Waste management
Concrete

optimizing and upgrading the CDW management in light of advanced technologies and steering the pathway for transitioning the EU towards a circular society.

Contents

1. Introduction

As the world moves towards its urban future, the linear economic model, the so-called "take, make, and dispose" pattern has achieved an unprecedented level of growth but has also burdened the anthroposphere with serious resource supply risks and waste generation pressure. The global resource extraction in 2015 is 13-fold higher compared to 1900, increasing from 7 Gt. to 89 Gt. (Aguilar-Hernandez et al., 2021). The global solid waste generation rate rose from fewer than 0.3 Mt. per day in 1900 to more than 3.5 Mt. per day in 2010, and it would double in 2025 and triple by 2100 (Hoornweg and Bhada-Tata, 2012).

An alternative "circular economy" would close loops in industrial ecosystems by applying a reduce-reuse-recycle (3Rs) principle that prevents the generation of wastes and turns wastes into resources. The circular economy originates from the "spaceship theory" introduced by ecological economist Boulding (1966), who perceived the earth as a circular system that has no exchanges of matter with the outside environment. This circular development model seeks to ultimately decouple global economic development from finite resource consumption.

Construction and demolition waste (CDW) is the primary waste stream of gross waste generation in modern society. The amount of CDW grows along with the current worldwide urbanization. China, the United States (US), and the European Union (EU) are the three biggest economies as well as the top three CDW generators (Kabirifar et al., 2020). The urban population in China increased from 35.88% in 2000 to 61.43% in 2020; while the US and the EU28 have relatively high urban population rates, 82.67% and 74.96% in 2020 (The World Bank, 2021).

With such a fast urbanization process, China was estimated to have a noticeable amount of CDW generation, approximately 1704 Mt., in 2018 (Qianzhan Industry Institute, 2019). However, china's current CDW recovery rate is less than 10% (Huang et al., 2018). As the US and EU28 are more developed and urbanized, they have much less CDW generated compared with China, 600 Mt. (EPA, 2020) and 372 Mt. (excluding excavated soils) (Eurostat, 2021a), respectively. The US and EU28 also have a better practice of CDW management. In 2018, the CDW recovery rate in the US is around 76% (EPA, 2020); it is even higher in the EU28, about 90% (Eurostat, 2021b). The high recovery rate of the EU28 results from its advanced CDW management system (Hao et al., 2020). Therefore, the policies, laws, regulations, and technologies for CDW management in the EU would be great references and lessons towards a circular construction sector.

The Waste Framework Directive 2008/98/EC (WFD) is seen as a milestone of modern waste management in the EU. One prominent contribution of the WFD is that it introduced the waste hierarchy. The first iteration of the WFD can be traced back to the 1975 Council Directive on Waste (75/442/EEC) (EC, 1975), in which methods for waste management were divided into (i) reduction in quantities of waste; and (ii) disposal via recycling and re-use, via recovery, and via storage and underground (see Fig. 2b). This description did not give a preference or hierarchy as to which method was preferable.

While the earliest hierarchy for waste management dates back to 1979 when a Dutch politician, Ad Lansink, proposed a concept "Ladder of Lansink" (translated from Dutch "Ladder van Lansink") in the Dutch parliament (Recycling.com, 2019). As a simple schematic illustration in Fig. 2a, the Ladder of Lansink clarified an order of preference for waste management and resource conservation options, with "reduce" at the top and "landfill" at the bottom. The principle of "Ladder of Lansink" has gradually evolved into what is known today as the waste hierarchy, and is an indispensable part of waste legislation, both EU-wide and globally. It was however not until 1991 that the WFD was updated to define concepts of disposal and recovery (91/156/EEC) (EC, 1991) as well as an optional priority to "prevention (or reduction)" and "recovery (by means of recycling, re-use or reclamation as well as the use of waste as a source of energy)" (illustrated in Fig. 2c).

It was not until the WFD 2008/98/EC, in 2008, that in the EU context the concept of a waste hierarchy was introduced, together with clearly defined a complete priority order for prevention and waste management operations, as shown in Fig. 2d. Most recently, Directive 2018/851 amended the WFD by significantly strengthening requirements on waste prevention (EC, 2018a). Compared with the 3Rs framework of circular economy, the waste hierarchy particularly considers the order of priority in waste handling through a five-stage plot pyramid from the most preferred option of "prevention" to the least preferred option of "disposal". The WFD also defined relevant concepts in waste management, such as "prevention", "recovery", and "end-of-waste criteria". Details of the explanation of those terms were included in the supporting information (SI).

In Europe, the construction sector is the biggest driver for resource consumption and waste generation, accounting for half of the resource extraction and one-third of all wastes (EC, 2014). Therefore, CDW was addressed as the key waste flow regarding waste management by the EU (Villoria Saez, 2011). To improve the circulation of materials in the construction sector, circular economy-inspired actions have been taken into account for CDW management (EEA, 2020). The history of circular economy dates back earlier than the waste hierarchy, but they share a similar goal of improving the effectiveness of waste treatment by reducing environmental impacts, mitigating resources depletion, and avoiding waste yields (Williams, 2015). A large number of studies have used the circular economy as an overarching paradigm for resource and waste management. However, discussions on the waste hierarchy are limited. CDW makes for a suitable case study because it is the largest waste stream in Europe and has been prioritized in the waste management plan of the EU (EC, 2020a). This study explores the practice of CDW management in Europe. The primary research question is: how is CDW in Europe managed based on the waste hierarchy? Five sub research questions (RQ) to be answered are listed as follows:

RQ1. How was the waste hierarchy further adopted in Europe?

RQ2. What is the connection between waste hierarchy and circular economy?

RQ3. How is CDW currently managed in each member state (MS) in view of the waste hierarchy framework?

RQ4. What are the technological routes for improved CDW management under the waste hierarchy framework?

RQ5. What is the future direction of CDW management in the EU?

2. Methods

This study presents an analysis of the development of the waste hierarchy and how the EU uses it to support CDW management in Europe. Note that excavated soil is excluded from this study. Methods used in this study include literature reviews, field surveys, and interviews of informants. The analytical framework and material sources of this study are described below.

2.1. Analytical framework

The analytical framework of this study mainly comprises three layers corresponding to Sections 3 to 5 as shown in Fig. 1. After the presentation of the methods, Section 3 presents the developmental trajectory of the waste hierarchy in Europe and identifies the connections between the waste hierarchy and circular economy. Then, Section 4 investigates the practice of CDW management in Europe. Based on the waste hierarchy, a maturity assessment was introduced to explore the general performance of CDW management in each EU MS. The situation of CDW prevention, CDW recovery, and CDW landfill of each MS was further investigated. Moreover, a brief overview of treatment methods for each constituent of CDW was conducted. Given that concrete is the primary waste stream of CDW, actions of waste concrete prevention and treatment were introduced in detail. Based on the outcome, Section 5 discusses the pathway for optimizing CDW management in Europe.

2.2. Data collection

Data was collected through literature reviews, field surveys, and face-to-face interviews. The literature for this study was gathered from multiple sources, including official documents and directives of the EU, reports of EU CDW management projects, and articles in journals. The EU WFD (2008) was taken as the basis for definitions of the waste hierarchy and other associated terms related to CDW management. Information on the developmental trajectory of the waste hierarchy and circularity framework was collected from EU documents and directives, as well as scientific articles. The process of the literature review is given in the SI.

EU project reports are also important material sources for this study. The evaluation of CDW management maturity of each EU MS was based on the report of the EU project "Resource Efficient Use of Mixed Wastes" (Monier et al., 2017). The status of CDW prevention (Eurostat, 2021c), CDW recovery (Eurostat, 2021b), and CDW landfilling (Eurostat, 2021b) in each MS was explored based on the data retrieved from the Eurostat. Technical details for CDW treatment were taken from four EU projects, namely the 7th Framework Program project C2CA, the EU Horizon2020 project HISER, the Horizon2020 project VEEP, and the EU Horizon2020 project ICEBERG.

Field surveys were conducted to investigate how CDW is processed at labs and on construction sites in Europe. As recycling technologies in those aforementioned projects were primarily developed and

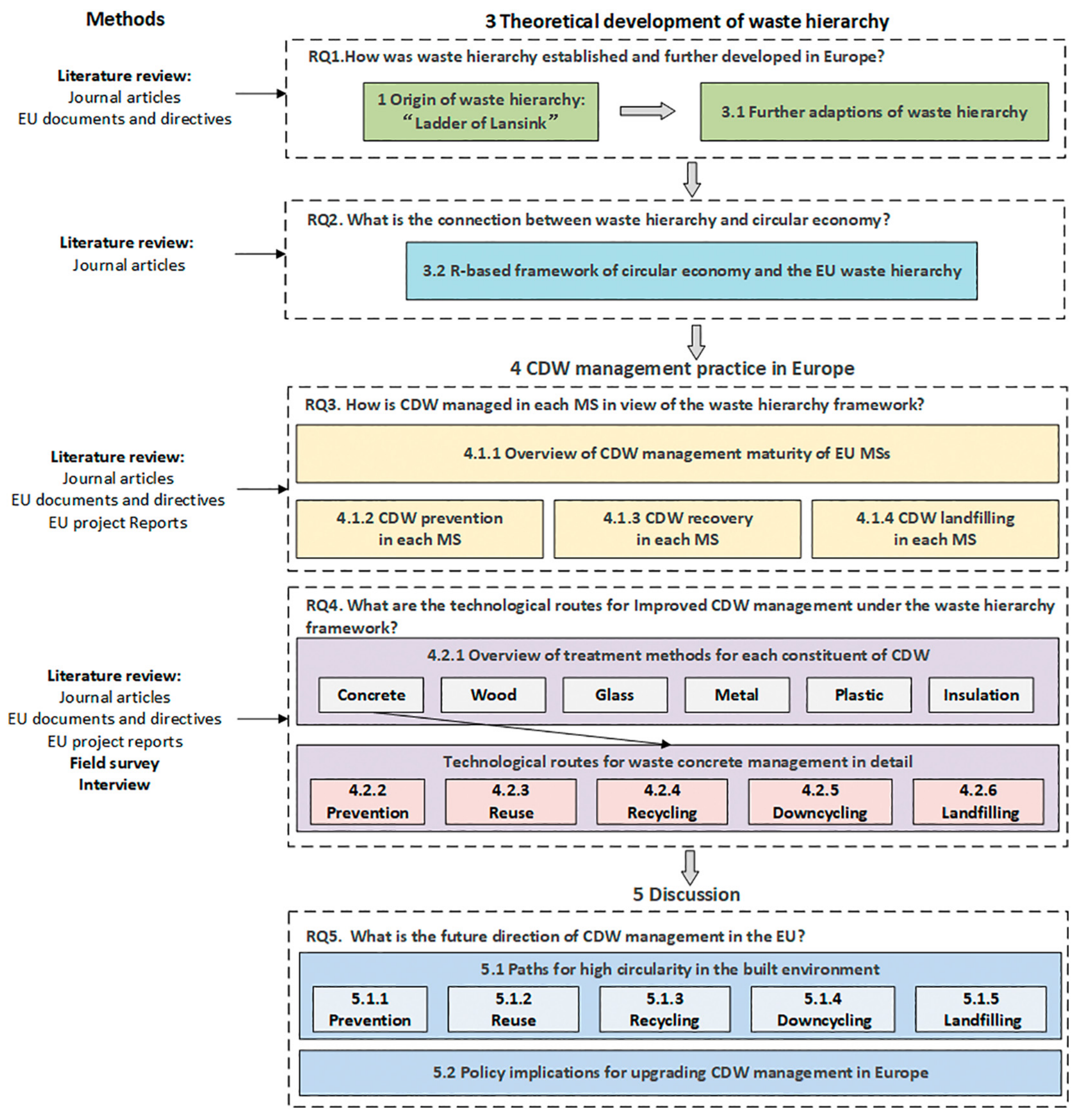


Fig. 1. Analytical framework of this study.

experimented in the Netherlands and Spain, we mainly conducted our field survey in these two countries. This includes trips to the CDW recycling plant of the Theo Pouw Group in Utrecht, the Netherlands; the Recycling Lab of the Delft University of Technology, the Netherlands; CDW processing site and pilot prefabrication construction site of the Strukton in Hoorn, Netherlands; pilot prefabrication construction site of the Technalia in Madrid and Bilbao, Spain. Interviews were held with participants within those EU projects, including managers from construction companies, developers and engineering of recycling facilities, researchers from universities and institutes, and officers from the Federation of the European Precast Concrete Industry.

3. Development of the waste hierarchy

This section gives further adaptions of the EU waste hierarchy and its relation with the circular economy.

3.1. Further adaptions of the waste hierarchy

While useful for understanding how to support circularity, the waste hierarchy is limited in its ability to address issues of minimizing environmental impacts and natural resource use (Gharfalkar et al., 2015; Price and Joseph, 2000; Van Ewijk and Stegemann, 2016). Practitioners and scholars in the field of waste management have tried to optimize the framework and clarify it for specific purposes. This section discusses examples of adaptions, improvements, and specifications of the waste hierarchy.

3.1.1. An additional bottom layer

Waste trafficking is a major issue today in some developing countries (Bartl, 2014). For example, disposal of CDW through illegal dumping and stockpiling is still a common practice in some suburbs of China (Zhang et al., 2018). This leads to risks to human health and environmental hazards. Bartl (2013) therefore recommended adding an additional layer of "trafficking" at the bottom of the EU waste hierarchy, as shown in Fig. 2e.

3.1.2. Context-specific waste hierarchies

Context-specific waste hierarchies are adapted regarding different waste categories, energy mixes, and treatment efficiencies and so on, therefore, not necessarily identical to the generalized waste hierarchy (Laurent et al., 2014). CDW is one of the largest waste streams in the EU. Elaborating on the Ladder of Lansink, Hendricks and Te Dordthorst (2001) recommended a "Delft Ladder" (see Fig. 2f, in which 10 waste treatment options are described for CDW management. Hendricks and Te Dordthorst (2001) further introduced a degradation model to

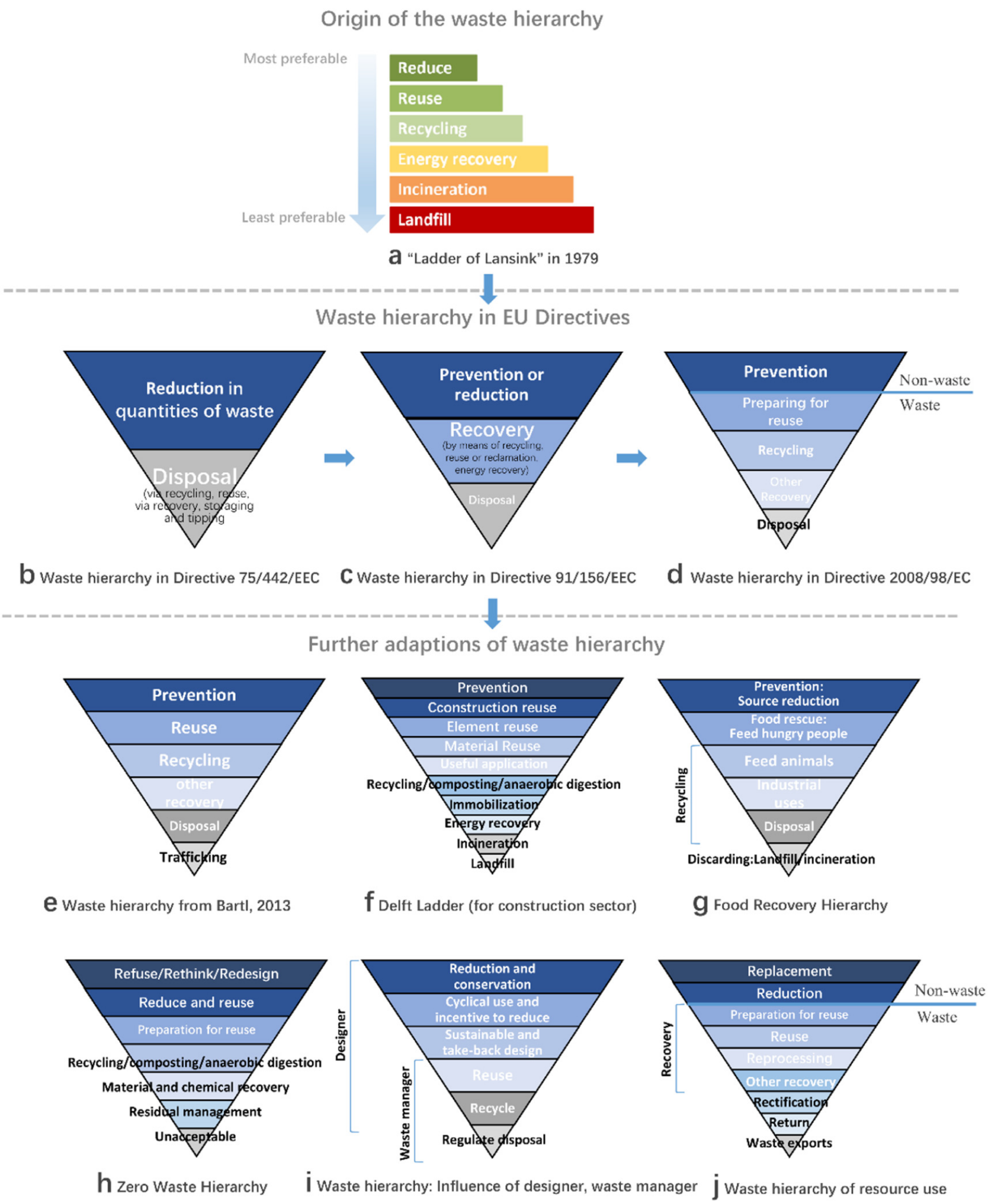


Fig. 2. Development of waste hierarchy in Europe. Note: Panel a was depicted based on the ladder of Lansink (Recycling.com, 2019); Panel b is designed based on the Directive 75/442/EEC (EC, 1975); Panel c was plotted based on the Directive 91/156/EEC (EC, 1991); Panel d was pictured based on the Directive 2008/98/EC (EC, 2008); Panel e is derived from Bartl (2013); Panel f is from Hendricks and Te Dordthorst (2001); Panel g is from the US Environmental Protection Agency's Food Recovery Hierarchy (Ceryes et al., 2021); Panel h was redesigned based on Zero Waste Hierarchy (2019); Panel i is from Cole et al. (2019); Panel j is a "hierarchy of resource use" proposed by Gharfalkar et al. (2015). Please note that the overview of those adoptions of the EU waste hierarchy is not exclusive.

systematically evaluate economic and environmental impacts associated with each option in the Delft Ladder. Beyond the construction sector, Papargyropoulou et al. (2014) extended the EU waste hierarchy for food waste management. The US Environmental Protection Agency also proposed a Food Recovery Hierarchy, as shown in Fig. 2g (Ceryes et al., 2021). Cole et al. (2019) introduced a hierarchy for waste electrical and electronic equipment and emphasizing the importance of design, as shown in Fig. 2i.

3.1.3. Emphasizing resource efficiency in the waste hierarchy

The driving factor of a waste hierarchy should not only be the environmentally sound disposal of waste but also ensure that the value of resources is preserved. Indeed, the EU waste hierarchy also considered matters beyond waste management, taking into account the resource use at product scale to reduce waste (see the "non-waste" in Fig. 2d). However, it still focuses on the recovery of waste and does not address the importance of design and resource efficiency in detail. To direct resource effectiveness into the EU waste hierarchy, Gharfalkar et al. (2015) proposed a hierarchy of resource use, as shown in Fig. 2j. This hierarchy of resource use clarifies key measures of resource/waste management, especially refining the contents of recovery. For example, "reprocessing" – which belongs to recovery operations– is divided into upcycling, recycling, and downcycling. Zero Waste Europe (2019) proposed a Zero Waste Hierarchy to shift the mindset from waste management to resource management. Fig. 2h illustrate that it differs from the EU waste hierarchy in the upper and lower levels, aiming to achieve value preservation by designing waste out of the system. The hierarchy of waste electrical and electronic equipment (see Fig. 2i) proposed by Cole et al. (2019) also emphasizes the significance of sustainable design in reducing waste.

3.2. The waste hierarchy and circular economy

Circular economy primarily appears in the literature through three main actions, that is, the 3Rs rule (Ghisellini et al., 2016). Apart from the EU, other countries such as China, Japan, the USA, Korea, and Vietnam also took the 3Rs and prioritized the “reduce” option as the essential principle for waste management policymaking (Sakai et al., 2011). The WFD introduced the fourth R “recover” as a 4Rs framework (Kirchherr et al., 2017) as the current EU waste hierarchy. Scholars extended the R-based circularity framework beyond the 4Rs, such as 5Rs (Gharfalkar et al., 2015), 6Rs (Yan and Feng, 2014), and 9Rs (9Rs(i) is from (Sihvonen and Ritola, 2015), and 9Rs(ii) is from (Potting et al., 2016)).

As shown in Fig. 3, the R-based principles of circular economy are highly related to the waste hierarchy. From a life cycle perspective, both the waste hierarchy and circular economy consider the whole life cycle of a product, including the pre-use phase, use phase, and post-phase. Both the waste hierarchy and circular economy have evolved over time to emphasize the design and use of a product before it turns into waste. Therefore, we can see that circular economy and waste hierarchy share a joint philosophy, aiming to manage waste by rethinking, redesigning, and repurposing in order to improve the resource effectiveness of a product and to reduce the generation and adverse impact of waste. The minor difference is that the waste hierarchy still allows disposal, while the framework of a circular economy does not.

4. CDW management practice in Europe in view of the waste hierarchy framework

4.1. Performance of CDW management in Europe

Via the aforementioned EU Directives, the waste hierarchy has an influence on waste management practices of the different EU MS. In this section, we evaluate the performance of CDW management practice in each European country after the introduction of WFD.

4.1.1. Overview of CDW management maturity of each European country

Monier et al. (2017) selected 13 indicators, such as CDW management legislation, waste policy, landfill management, recycling and reuse practice, and waste prevention to comprehensively evaluate the maturity level of CDW management in each MS of the EU28. The results are shown in Fig. 4a. MSs in Northern and Western Europe have a higher score. The Netherlands has the highest score, indicating the best CDW management practice over other MSs. Among the 13 indicators, those related to actions in the waste hierarchy are presented in Fig. 4a, namely prevention, recovery, and landfilling. The maturity level of these three indicators varies between MSs. The Netherlands, UK, Denmark, and Luxembourg are considered to be at the top level of improving and optimizing all of the CDW practice categories that relate to CDW prevention, CDW recovery, and CDW landfilling.

4.1.2. Prevention of CDW generation in each European country

Waste prevention is the prime tenet of the waste hierarchy. In the waste prevention programs of some MSs, CDW prevention is often measured through the reduction of the quantity of generated CDW. For example, France aimed to stabilize the generation of CDW by 2020; Sweden intended to reduce CDW yield per floor area compared with 2014; Wales set a prevention goal by reducing CDW by 1.4% every year to 2050 compared to the 2006 level (Monier et al., 2017). In this section, an estimation of the trend of per capita CDW generation was conducted to reflect the CDW prevention in each MS.

Eurostat does not have direct statistics on the amount of CDW. Mineral waste is the main waste stream of CDW by weight, accounting for over 80% of the total CDW generated in the EU (Monier et al., 2017). Therefore, estimation of the CDW generated in each MS is performed by referring to the mineral waste from construction and demolition. Fig. 4b illustrates the CDW generated in each MS. The EU28 yielded approximately 372 Mt. in 2018 (Eurostat, 2021c), while the gross CDW generation almost triples (977 Mt) if excavated soils are accounted for. The CDW generated in Germany, France, the UK, Italy, Netherlands, and Spain sum up to 88% of the gross CDW in the EU28. Some MSs still present an ascending trend of CDW generation, such as Malta, Austria, Belgium, Estonia. Some MSs remain relatively steady,

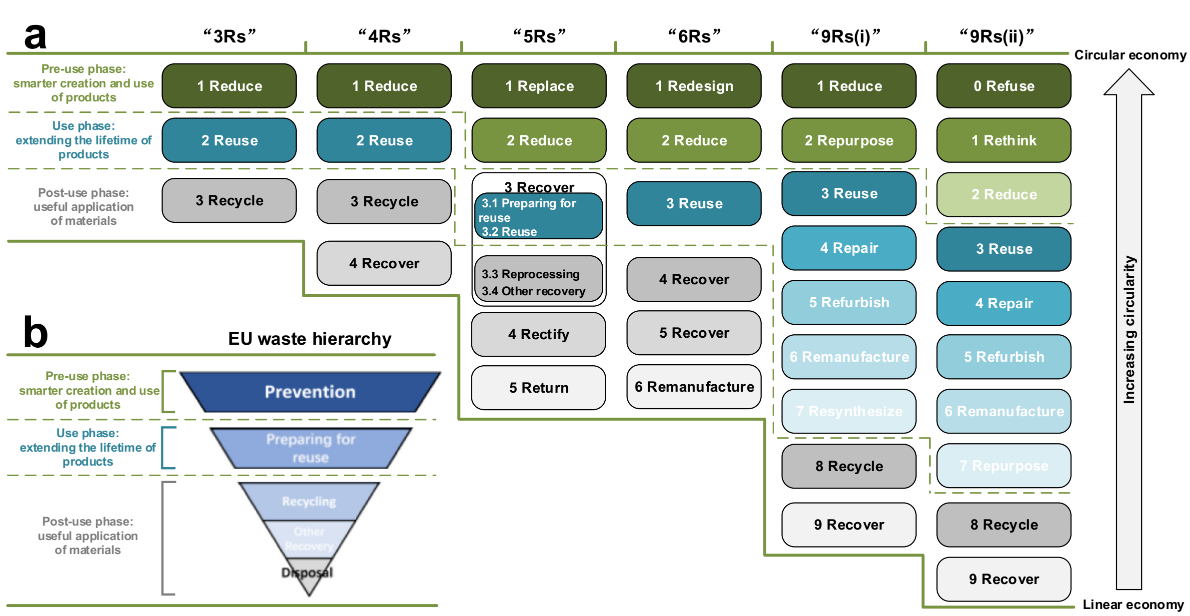


Fig. 3. Comparison of (a) circular economy and (b) waste hierarchy framework. Source: 3Rs (Ghisellini et al., 2016); 4Rs (Kirchherr et al., 2017); 5Rs (Gharfalkar et al., 2015), 6Rs (Yan and Feng, 2014), 9Rs(i) (Sihvonen and Ritola, 2015); 9Rs(ii) (Potting et al., 2016); EU waste hierarchy (EC, 2008).

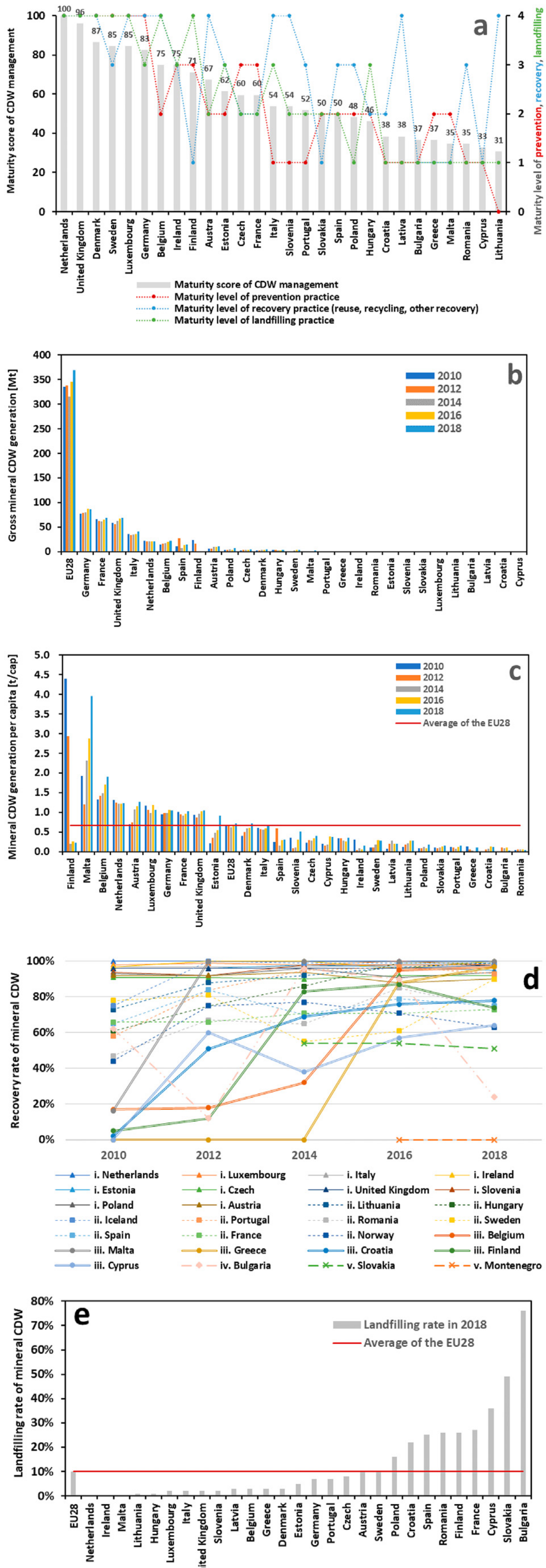


Fig. 4. (a) Maturity level of construction and demolition waste (CDW) management, (b) Gross and (c) per capita mineral CDW generation, (d) recovery rate of non-hazardous mineral CDW, (e) landfill rate of non-hazardous mineral CDW of the EU28. Panel (a): for maturity score in the left axis: the original score is 52 in total (Monier et al., 2017), which was up-scaled to 100 in this study. For maturity level at the right axis: Level 0 denotes "information not available"; Level 1 represents "initial level"; Level 2 indicates "developing level"; Level 3 denotes "implemented level"; Level 4 manifests "improving and optimizing level". Panel (b): data on the gross mineral CDW generation in Europe were collected from Eurostat (2021a). Panel (c): the CDW per capita was obtained by dividing gross mineral CDW generated in each MS in Panel (a) divided by its population (2021c). Panel (d): 28 European countries were included, 25 EU MSs and three non-MS European countries Iceland, Montenegro, and Norway (Eurostat, 2021b). Panel (e): landfill rate is estimated based on the recovery rate of the European countries in 2018 in Panel (d).

such as Luxembourg, Germany, France, Netherlands, and the UK. Other MSs show a fluctuating tendency, such as Slovenia, Spain, Latvia, Ireland, and Greece. Finland presents a steep decline after 2010, which is likely to be the result of intense demolition activities prior to 2010, rather than prevention strategies.

Based on the population of each MS (Eurostat, 2021d), the CDW generation per capita varies between 0.1 t/cap and 4.5 t/cap (as shown in Fig. 4c), with an average level of 0.7 t/cap. This coincides with the Deloitte's report (Iacoboaea et al., 2019) about the quantity of CDW/cap of each MS in 2012, which ranges from 0.1 to 3.9 t/cap. The distinctive differences may result from the following several reasons. First, different statistic calibers and methods may lead to results. The statistic of CDW generation in some MS has a break in the time series or is provisional. Besides, only mineral waste from construction and demolition is accounted for. Second, uncommonly extensive construction, renovation, demolition, and rehabilitation activities in a specific year can affect the CDW generation per capita in that year. For instance, 2010 and 2012 of Finland, and 2016 and 2018 of Malta are obvious outliers. Third, building structure and design, material use, and housing floor area per capita also influence the CDW generation per capita.

4.1.3. Recovery of CDW in each European country

The recovery rates of 28 European countries are shown in Fig. 4d, and were estimated based on the recovery of non-hazardous mineral CDW (Eurostat, 2021b). European countries can be categorized into five types with regards to CDW recovery rate: (i) highly developed, (ii) developed, (iii) fast-developing, (iv) fluctuating, (v) slow-developing. The highly developed countries have recovery rates over 90% since 2010, such as the Netherlands, Luxembourg, Italy, Ireland, and United Kingdom. Highly developed countries accounted for 10 of the 28 cases. The developed countries represent the recovery rates of states that were between 40% and 80% in 2010 and increased to 60%-100% in 2018, such as Iceland, France, and Sweden, amounting to 9 of the 28 cases. A fast-developing country denotes the recovery rate of a state that was below 20% in 2010 and rapidly increased to 60% in 2018, for instance, Belgium, Finland, Greece, and so on, adding up to 6 of the sample space. The only fluctuating country is Bulgaria, whose recovery rate fluctuated between below 20% and 90% during 2010-2018. The recovery rates of slow-developing countries Slovakia and Montenegro stayed below 60% until 2018. In general, based on the treatment of non-hazardous mineral waste, the EU28 had excellent performance over CDW recovery, with an average recovery rate of 90% in 2018 (Eurostat, 2021b). However, it shows a clear differentiation of CDW recovery in Europe, with the recovery rate of the Netherlands at 100% since 2010, whereas Montenegro remained at 0% in 2018 as most of the CDW was landfilled.

4.1.4. Landfilling of CDW in each European country

Disposal is the least preferable action in the waste hierarchy and should always be avoided. With the exception of a few CDW materials, such as woods and plastics, which are combustible, most CDW is inert and is disposed of through landfills. As the data of CDW landfilling for EU MSs is not available, the recovery rate in Fig. 4d is used for estimating the landfill rate. It was assumed that the unrecovered CDW is disposed of by landfilling. The landfill rate of CDW of each MS is shown in Fig. 4e. The EU28 MSs have a desired overall control on landfilling of non-hazardous mineral CDW, with an average landfill rate of 10%. With the exception of Cyprus, Slovakia, and Bulgaria, the landfill rates of the remaining 25 MSs were below 30%.

4.2. Technological routes for improving CDW management under the EU waste hierarchy framework: the case of concrete

Treatment methods (reuse, recycling, other recovery, and disposal) of the main compositions of CDW are presented in this section. Concrete and other stony accounts for over 80% of CDW by weight in Europe (Zhang et al., 2020b). Methods for the prevention, reuse, recycling, downcycling, and disposal of waste concrete are elaborated in this section.

4.2.1. Overview of treatment for the main constituent of CDW

CDW consists of different categories of materials, depending on sources, size, location, and type. A review of the literature (Dong et al., 2017; Gálvez-Martos et al., 2018; Kartam et al., 2004; Kleemann et al., 2016; Kourmpanis et al., 2008; Lawson et al., 2001; Mália et al., 2013; Martínez Lage et al., 2013; Silva et al., 2017; Villoria Sáez et al., 2018; Villoria Saez, 2011; Wang et al., 2019; Zhang et al., 2020b) with data on CDW composition shows that CDW contains concrete and other stony waste, metal, asphalt, wood, glass, plastic, and insulation. Asphalt is excluded in the current analysis because it is usually used in infrastructure projects such as highways, pavements, car parks, and driveways.

Based on the structure of waste hierarchy (see Fig. S1), treatment methods are divided into preparing for reuse, recycling, other recovery, and disposal, illustrated in Table 1. Details and information sources are presented in the SI. CDW prevention was not included and is elaborated in the next section. Gharfalkar et al. (2015) also extended the content of recycling with the concepts of "upcycle" and "downcycle", depending on the purpose/value of the secondary product compared to that of the original production. It is noteworthy that according to the definition of recycling in WFD, recovery also included upcycling and downcycling. For example, processing waste concrete for road base construction is downcycling; processing waste glass as a substitute for additives in concrete production could probably be termed upcycling.

4.2.2. Prevention of waste

Based on the EU waste hierarchy, there are three aspects to preventing waste concrete: reduction of quantity, reduction of adverse impact, and reduction of harmful content. Strategies for waste concrete prevention include Eco-design, smart dismantling, and selective demolition, and are listed in Table 2.

The prevention of CDW largely depends on product design, with prefabricated designs being well placed to reduce CDW (Tam et al., 2006). In the construction phase, prefabrication buildings can minimize construction waste intensity from 0.91 to 0.77 ton/m^2, compared to conventional buildings (Lu et al., 2021). Regarding concrete, the use of prefabricated concrete elements is expected to halve the generation of waste concrete(Tam et al., 2005). Designing out waste (DOW) is a similar concept originating from England and Ireland, which aims to influence waste arising later in the life cycle of a building when it is refurbished or demolished (WRAP, 2009).

In the use phase, enhancing the durability of buildings, components, and materials is a universally acceptable way of minimizing waste generation. Extending the life span means that it will take a longer time to replace them with newer ones and thus less waste is produced (Silva et al., 2017). Similarly, lightweight design can reduce total material requirements by 25–30% (Carruth et al., 2011).

In the EoL phase, a dismantable and recyclable building system will allow elements and components to be reused, while the materials are also easily separable during dismantling and demolition. Such design schemes are known as design for dismantling (DFD), design for recycling (DFR) (Hendricks and Te Dordthorst, 2001), and design for deconstruction (D4D) (Monier et al., 2017).

Beyond design, smart dismantling and selective demolition will also reduce EoL materials ending as waste. Smart dismantling and selective demolition prioritize the collection of products and components rather than directly recycling and recovery. Dismantling is a process prior to demolition, that aims to remove the attachment materials and facilities, such as carpets, lamps, paperboards, and doors from the skeleton of the building in an intact manner. Smart dismantling means a well-designed and well-organized dismantling scheme, as introduced by the C2CA project. Smart dismantling can remove 90–95% of the CDW mix at the dismantling stage. This compares favorably to the common practice in the Netherlands, in which only about 80–85% of the CDW mix can be removed through dismantling. Hazardous waste such as asbestos should be removed before dismantling by specialized workers.

After dismantling, selective demolition is applied to destruct the target building and keep the non-stony stream from waste concrete. In the Netherlands, selective demolition can remove 40% of wood, 50% of plastics, and 50% of steel attached to the stony structure (Hu and Kleijn, 2016).

4.2.3. Reuse of waste concrete

According to the WFD (EC, 2008), reuse of waste concrete can be defined as "any operation by which EoL concrete products/elements/components that are not waste are used again for the same purpose for which they were conceived". We note however that reuse of entire structural concrete components is extremely rare because structural components/elements such as beams, columns, walls, and floor slabs are often designed to resist very specific loading, thus limiting the opportunities for reusing them (Purnell and Dunster, 2010). Moreover, structural damage may be incurred when separating cast-in-situ structures. Therefore, renovation and retrofitting a building seems a more feasible option. The VEEP project is currently conceiving a dismountable precast concrete element system for new building construction (Zhang et al., 2020a) and existing building retrofit (Zhang et al., 2021a, 2021b). The details were given in the IS.

4.2.4. Recycling of waste concrete

Based on the definition of recycling in the WFD (EC, 2008), recycling of concrete can be described as any operation by which waste concrete is reprocessed into products and materials for making new concrete. Four technological systems for recycling concrete are discussed in this section: wet processing system, advanced dry recovery system (ADR), thermal separation system, and smart crushing system (SCS). The sketches and their main features of the wet processing system, ADR system, HAS system, and the SCS are summarized in Fig. 5 and Table 3. The details of the four systems were in the IS.

4.2.5. Downcycling of waste concrete

Backfilling is the commonest method for downcycling waste concrete. WFD 2008/98/EC defined backfilling as "reclamation in excavated areas or for engineering purposes in landscaping" (EC, 2011). Backfilling of CDW is alternatively called "downcycling" (Zhang et al., 2020b) or "low-quality recovery" (Monier et al., 2017).

Since backfilling counts as a form of recovery, it is considered the main way to achieve the EU 70% target for CDW. Downcycling can be either deployed on-site with a mobile crusher or off-site with a stationary plant. Monier et al. (2017) categorized backfilling to be compliant with the WFD backfilling criteria: (i) reclamation of excavated areas (in construction); (ii) reclamation of excavated areas (mines and quarries); (iii) landscape engineering; (iv) covering landfills.

Table 1
Preparing for reuse, recycling, other recovery, and disposal of the main compositions in CDW based on the EU waste hierarchy. Note: Information was mainly collected from (NFDC, 2020).

	Concrete and other stony waste	Metal	Wood	Glass	Plastic	Insulation
Preparing for reuse	prefabricated concrete products and elements (walls, floors, stairs, floors, etc.) may be reused	(i) steel-section element could be reused; (ii) whole portal frame buildings can be reclaimed for reuse	dimensional timbers, chipboards, timber doors, windows, and floorboards could be reused	glass panes and panels could be reused	plastic pipes and claddings could be reused	insulation layer in building elements could be reused
Recycling	processed as feedstock in new concrete production	re-melted to produce new ferrous products	recycled as feedstock in new wooden products	recycled as feedstock for new vitreous products	processed as a feedstock for producing new plastic products	recycled for producing new insulation
Other recovery	downcycled for other applications instead of making new concrete	No recovery options for steel.	(i) energy recovery; (ii) chipped as an organic mulch in gardening, landscaping, (iii) compost	(i) crushed for backfilling; (ii) ground and refined as feedstock for making concrete and aerogel	energy recovery	(i) energy recovery (ii) processed as additives for producing concrete
Disposal	should always be avoided	should never be considered	should always be avoided	should always be avoided	should not be considered	should always be avoided

4.2.6. Landfilling of waste concrete

Concrete is recyclable and should not be disposed of unless it is mixed with inseparable contaminants, such as paints and heavy metals. Fig. 4e illustrates that waste concrete is still disposed of by landfilling in some European countries. According to the EU's Landfill Directive (EC, 1999), the contaminated concrete must be treated and meet certain sanitary requirements. In some cases, waste concrete is also disposed of via foundation elevation on-site instead of in a landfill site. This kind of backfilling, known as backfilling without useful application, differs from backfilling for road base construction and is therefore also considered as landfilling. The difference between landfilling and useful backfilling is that useful backfilling aims to fulfill a specific function – substituting non-waste resources – while landfilling or backfilling without useful application solely aims to get rid of waste concrete.

5. Discussion

The waste hierarchy only provides a very general guideline for CDW management. Policy formulation for each action in the waste hierarchy is flexible regarding specific situations (Rasmussen et al., 2005). In this section, we discuss the future paths and potential policy implications for optimizing CDW management in the EU.

5.1. Paths for improving the circularity of the construction sector in the EU

Base on the five layers in the EU waste hierarchy, future pathways for improving the circularity of the construction sector in the EU are discussed.

Table 2
Strategies for prevention of waste concrete.

	Strategies at the design stage	Strategies at the EoL stage
Reduction of quantity	Long-lasting design, lightweight design, design for dismantling (DFD), design for deconstruction (D4D), design for recycling (DFR), designing out waste (DOW)	Smart dismantling, selective demolition
Reduction of adverse impact	DFD, D4D, DFR, DOW	Smart dismantling, selective demolition
Reduction of harmful content	DFD, D4D, DFR, DOW	Smart dismantling, selective demolition

5.1.1. Prevention: still the highest priority

In the waste hierarchy, waste prevention is perceived as the most preferable option. For the construction industry, CDW prevention is mainly measured through the reduction of waste in mass by using the indicators of raw material extraction, CDW generation, and physical functions provision. According to the estimation in Fig. 4b, CDW generation in the EU28 has stabilized approximately 350 Mt. but does not show a decreasing trend. Reducing the CDW in mass should be the primary target of CDW management in future.

5.1.2. Preparing for reuse: promising in the future but challenging now

Reuse in the context of CDW can often be observed in electrical and electronic equipment and furniture when a building is demolished. The Irish Project ReMark aims to boost the market for secondary or repaired goods by creating a reusing standard that can be applied to deal with reused products (EC, 2019). A “ReMark” logo is used to certify reused goods with safety and quality. Analogously, Scotland implemented a “Revolve” quality standard for trading reused goods (Zero Waste Scotland, 2021). Beyond the reuse of components, the prevalence of prefabrication design for new constructions in Europe is a good sign for the potential reuse of construction elements in the future. However, the reuse of building elements is still rare due to the bulkiness and technical difficulty. Elements to be reused need strict requirements for structural integrity when dismantling, transporting, and storing. Structural concrete elements have even stricter requirements for reuse than non-structural ones. Key solutions to boosting reuse in the building industry lie in technological innovation, quality certificates, and standardization.

5.1.3. Recycling: a step towards a circular society

High value-added recycling is the next key step to a circular society. Whether or not a waste is recycled is subject to multiple factors, such as end-of-life conditions, the function of materials, marketing of secondary materials, and efficiency of a treatment process. To overcome obstacles to recycling, on the one hand, on-site CDW separating is needed to assure the quality of waste; on the other hand, the cost-effectiveness of recycling systems should also be considered.

5.1.4. Downcycling: the current main outlet

Downcycling is a critical connection between disposal and recycling. Downcycling CDW for road base construction is, and in the near future still will be, the primary approach for CDW management in Europe. For instance, although the Netherlands has a 100% recovery rate, over 95% of waste concrete is downcycled. Countries that still have a high

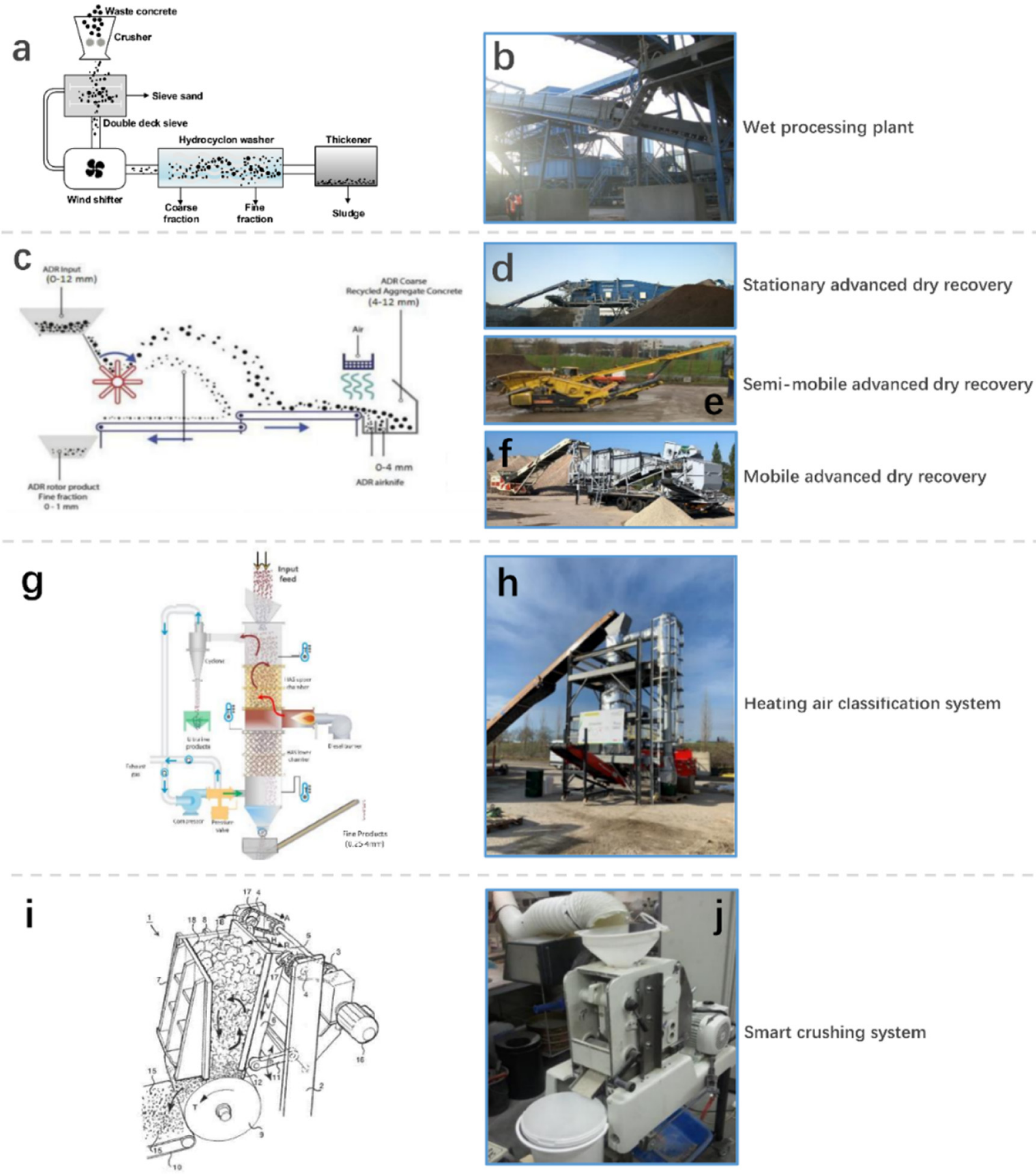


Fig. 5. Sketches of different concrete recycling systems. Note: Panel (a) depicts the sketch of the simplified wet processing system which was plotted based on (Hu and Kleijn, 2016; Zhang et al., 2019). Panel (b) shows a Theo Pouw wet processing plant on-site in Utrecht, Netherlands. Panel (c) visualizes the sketch of advanced dry recovery (ADR) (Somi, 2016). Panel (d) is a stationary ADR on-site in the Theo Pouw Eemshaven plant, Netherlands (Hu and Kleijn, 2016). Panel (e) presents a semi-mobile ADR on-site in Hoorn, Netherlands. Panel (f) shows a mobile ADR on-site in Hoorn, Netherlands. Panel (g) manifests the sketch of the heating air classification system (HAS) (Gebremariam et al., 2020). Panel (h) shows a HAS facility at site in Hoorn, Netherlands (Gebremariam et al., 2020). Panel (i) illustrates the sketch of the smart crushing system (SCS) (Ning, 2012). Panel (j) shows the SCS from the SmartCrusher BV.

Table 3
Summarization of technological systems for recycling waste concrete. Note: "√" represents one recycling system having the feature; "×" denotes one recycling system not having this feature.

Features	Wet process	Stationary/semi-mobile ADR	Mobile ADR	HAS	SCS
Transportability	×	×	√	√	√
Fully recycling	×	×	×	√	×
Producing recycled clean gravel	√	√	√	√	√
Producing recycled clean sand	×	×	×	√	√
Producing recycled cementitious material	×	×	×	√	√
Generating by-product: sieve sand	√	√	√	×	√
Generating waste: sludge	√	×	×	×	×
Energy resource	Electricity	Diesel and electricity	Diesel and electricity	Diesel	Electricity
Capacity	150 t/h	130 t/h	50 t/h	3 t/h	20 t/h

landfill rate, such as Cyprus, Slovakia, and Bulgaria, should be strongly encouraged by the EU to achieve the 70% goal by improving downcycling practice; while MSs like the Netherlands, Luxembourg, and Ireland should be expected to transition to cost-effective recycling rather than downcycling.

5.1.5. Landfilling: to be eliminated

Except for a small number of MSs, the overall landfilling rate of mineral CDW of the EU28 is low. This results from the fact that mineral CDW is chemically inert, and is thus relatively easy to recover. The situation of non-mineral waste is less positive. Except for a small number of MSs (Netherlands (3%), Denmark (3%), Belgium (4%), Slovenia (5%), Sweden (8%), and Austria (9%)), the landfilling rates of non-mineral waste (not only CDW) of the rest are higher than 10% and 11 of them were higher than 30% in 2016 (Eurostat, 2021e). landfilling of CDW is expected to be gradually replaced by at least downcycling routes in the near future.

5.2. Policy implications

5.2.1. Set ambitious targets

At an EU-wide, more ambitious quantitative targets are supposed to be set for prevention, reuse, and recycling. The WFD requires MSs to achieve at least 70% of the CDW recovery rate by 2020. Eurostat has not published the recovery rate for 2020. It can be seen from Fig. 4d that most MSs would realize the 70% target in 2020. Therefore, quantified targets for prevention, reuse, and recycling should be established in the next amendment of the WFD.

5.2.2. Promote ecodesign and waste separation

Promoting waste prevention is essential for the circularity of the construction sector. The WFD requires that MSs of the EU must establish their waste prevention programs by the end of 2013, which will be assessed and amended every sixth year (EC, 2008). These national programs consist of five phases: (i) evaluation of the situation, (ii) prioritization, (iii) strategies setting, (iv) planning and implementation, and (v) progress reporting. Regarding phase iii, there are mainly three strategies for waste prevention: informational strategies, promotional strategies, and regulatory strategies (EC, 2009). Prospective CDW prevention can be realized by the promotional approach, such as promotion of the eco-design of buildings (as summarized in Table 2) and the regulatory approach by compelling the implementation of on-site dismantling, sorting, and selective demolition. Separating CDW on-site is indispensable to assure further reprocessing, as quality requirements of waste for recycling or reuse can be harshly rigorous sometimes. For example, less than 1% of non-stony materials are allowed in the recycled concrete aggregate, because non-stony residue, such as glass, would interfere with the alkali-silica reaction in new concrete products (Hendriks and Janssen, 2001). This indicates contaminants have to be separated before waste is recycled by on-site dismantling, sorting, and selective demolition.

5.2.3. Implement incentive measures

Incentive measures may be considered to boost the development of prevention, reuse, and recycling. This may include financial incentives, such as tax reduction, grants for researching and developing innovative technological systems or market investigation, subsidies and low-interest loans for purchasing deploying recycling and reuse technics. Other potential incentive strategies are sustainable public procurement that requires recycled and reused content, and green material or eco-product labels, etc.

5.2.4. Establish quantitative assessment index

It is also important to establish a quantitative assessment index for supporting the implementation of the waste hierarchy regarding different localized characteristics. On the one hand, prioritization of each layer in a waste hierarchy is determined based on its environmental and/or economic benefits. However, recycling is usually costly, and can be even costlier than disposal in some areas (Tonjes and Mallikarjun, 2013). In addition, recycling may also bring about potential side effects that lead to higher environmental impact (Zink and Geyer, 2017). Therefore, establishing standardized life cycle assessment and life cycle costing based tools for assessing alternative CDW treatment options can support environmental and financial performance-based policy-making for material circularity. On the other hand, treatment options are also dependant on the demand of secondary markets in a region. For instance, CDW is more inclined to be recycled as concrete aggregate in countries that are having extensive house construction activities; CDW may end up as road base filler in countries that are experiencing large-scale infrastructure expansion. Hence, analyses of supply and demand conditions of secondary markets are also needed for specifying the EU waste hierarchy in a localized situation.

5.2.5. Restrict landfilling

In addition, restrictions on CDW landfilling should be further enhanced. The level of recovery is directly correlated with restrictions on landfilling. For instance, the Netherlands has the best practice of CDW recovery. The high recovery rate of CDW in the Netherlands is the consequence of its long-standing landfill restrictions (Lieten and Dijcker, 2018). Since the introduction of the landfill tax in 1995 and the landfill ban in 1997, landfilling of CDW in the Netherlands has been reduced significantly (Scharff, 2014). Landfill Directive 1999/31/EC was introduced EU-wide two years later after the Dutch landfill ban (EC, 1999). The EU landfill law aims to reduce negative environmental impacts from landfilling with stringent technical requirements. However, it does not prohibit the landfilling of recyclable materials. To eliminate landfilling, the EU enacted the Directive (EU) 2018/850 to complete the Landfill Directive by introducing restrictions on landfilling of materials that are recyclable or energy-recoverable by 2030 (EC, 2018b). A circular economy action plan was also launched in 2020 to courage the roader application of well-designed economic instruments, such as landfill tax under the EU Taxonomy Regulation (EC, 2020b).

6. Conclusions

This study used the waste hierarchy as an overarching framework to explore the practice of CDW management in Europe. Materials were collected through literature reviews, field surveys, and face-to-face interviews. This study first investigated the establishment and development of the waste hierarchy in Europe. The waste hierarchy originated from the Ladder of Lansink, which was named after the Dutch politician who devised it. The waste hierarchies subsequently adopted by scholars and practitioners have been more concerned with waste prevention and resource efficiency than just waste management. The circular economy shares a similar evolutional trajectory as the waste hierarchy. Both waste hierarchy and circular economy envision a new way of waste management by rethinking, redesigning, and repurposing products in order to improve the resource effectiveness and to reduce the generation and adverse impact of waste from the life cycle of pre-use, use, and post-use phases.

This study assessed the general maturity level of CDW management of each MS. The maturity score of each EU MS differs significantly between MSs. Countries in North-Western Europe have a better overall practice of CDW management. Detailed CDW generation, recovery, and landfill of each MS were also explored. The EU28 has a desired recovery rate and a low landfill rate in general. However, it can be noticed from the trend of CDW generation that many EU MSs do not show an obvious advancement in waste prevention. Regarding the treatment methods of CDW, novel technological systems are developed in several EU projects. Such technical innovations mainly focus on cost-effective concrete recycling and prefabrication construction. Finally, a discussion was conducted to summarize the future direction and potential policy implications for optimizing CDW management in Europe.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the support of the EU 7th Framework Program project C2CA "Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste" (No. 265189), EU Horizon 2020 project HISER "Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste" (No. 642085), EU H2020 project VEEP "Cost-Effective Recycling of C&DW in High Added Value Energy Efficient Prefabricated Concrete Components for Massive Retrofitting of our Built Environment" (No. 723582), and the EU Horizon2020 project ICEBERG "Innovative Circular Economy Based solutions demonstrating the Efficient recovery of valuable material Resources from the Generation of representative End-of-Life building materials" (No. 869336). The first author appreciates the support of the China Scholarship Council (No. 201706050090).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.149892.

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