Science of the Total Environment 944 (2024) 173859

Contents lists available at ScienceDirect

Science of the Total Environment

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

Management of excavated soil and dredging spoil waste from construction and demolition within the EU: Practices, impacts and perspectives

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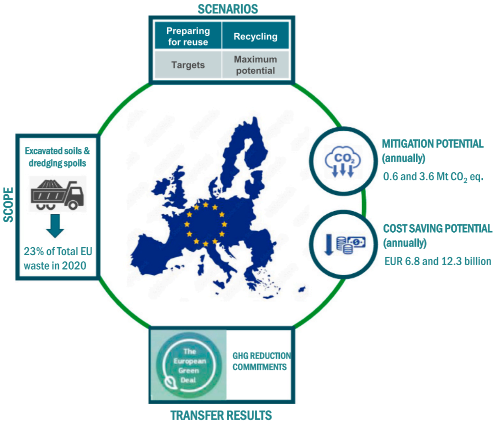
HIGHLIGHTS

- Excavated soil and dredging spoil account for 23 % of the total EU waste generation.
- Circular strategies have great potential for environmental and economic benefit.
- Life cycle assessment and costing quantifies likely environmental and cost savings.
- Preparing for reuse and recycling lead to savings of up to 3.6 Mt. CO_2 eq. annually.
- Economic savings could be between EUR 6.8 and 12.3 billion annually.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Philiswa Nomngongo

Keywords:
Recycling
Excavated soil
Dredging spoil
LCA
LCC
Europe

ABSTRACT

Excavated soil and rock (ESR) and dredging spoils (DDS) account for 23 % of the total EU waste generation in 2020. This study performs a life cycle assessment and life cycle costing to quantify the potential environmental and cost savings resulting from increasing the level of ESR and DDS prepared for reuse and recycled in comparison to the business-as-usual practice. Scenarios for the waste management pathways based on the *status quo*, technical feasibility or normative impositions are assessed, including the potential contribution to achieving the European Green Deal goals. Results show that promoting preparing for reuse and recycling could lead to non-negligible GHG reductions (up to 3.6 Mt. CO_2 eq.) and economic savings (EUR 12.3 billion) annually. Depending upon the scenario, 0.2 % to 1 % of the net annual GHG emissions reductions sought by the European Green Deal could be facilitated by scaling up improved circular management of ESR and DDS at the EU level. Finally, the study highlights the main barriers to scaling up to more circular (i.e., preparing for reuse and

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https://doi.org/10.1016/j.scitotenv.2024.173859
Received 18 March 2024; Received in revised form 23 May 2024; Accepted 6 June 2024

recycling) and better performing management options in Europe. The results provide new insights for the European Green Deal and circular economy policymaking for CDW.

1. Introduction

Excavated soil and rock (ESR) and dredging spoils (DDS) account, respectively, for 20 % and 3 % of the total EU waste generation (444 and 79 Mt), that is, about 52 % and 9 % of the construction and demolition waste (CDW) generated in the EU in 2020 (848 Mt) (Cristóbal García et al., 2024). Despite their significant volume, ESR and DDS are usually excluded from policy measures and recovery targets, such as the Waste Framework Directive (WFD - Directive 2008/98/EC) recovery target of 70 % of CDW by 2020. Significant quantities of ESR and DDS are still landfilled rather than reused or recycled. The main research questions addressed in this study are: What are the missed opportunities from the current suboptimal management of excluding ESR and DDS? What are the potential benefits and barriers to including ESR and DDS in policies that encourages best practice management on a larger scale?

In view of possible future updates of the EU regulatory framework for ESR and DDS, this article: a) quantifies the ESR and DDS waste generation for the EU Member States; b) identifies relevant best practice management pathways for ESR and DDS; c) reviews the scientific literature to identify research gaps and barriers to more circular management; and d) performs a life cycle assessment (LCA) and life cycle costing (LCC) to quantify the potential environmental and cost savings resulting from increasing the level of ESR and DDS prepared for reuse and recycled in comparison to the business-as-usual practice. The authors selected LCA because it is regarded as a comprehensive tool to assess the environmental impacts of end-of-life treatments at the level of society, as well as a suitable tool to assess the environmental performance of the movement towards a more circular economy (Haupt and Zschokke, 2017). Besides, life cycle thinking and LCA are vital elements of sustainability assessments, and the European Commission has included them in the Better Regulation toolbox.

Therefore, the purpose of this article is to contribute to the scientific analyses underpinning the assessment of policy measures for ESR and DDS. The results show that scaling up more sustainable and circular management of ESR and DDS in the EU achieves greater resource efficiency, environmental, and economic benefits. The analysis provides new insights for the EU's Green Deal and circular economy policymaking in relation to CDW management.

1.1. Literature review

Recently, Scialpi and Perrotti (2022) and Crocetti et al. (2022) performed a general review of the state-of-the-art and novel trends in sustainable and circular management of ESR and DDS. The literature review herein conducted is focused on circular strategies (i.e., preparing for reuse and recycling) as well as recovery (i.e., backfilling) and landfilling. Few studies in the literature have evaluated the environmental (mainly global warming potential (GWP) and energy consumption) and economic impacts of managing these two CDW fractions and these are usually restricted to recycling and landfilling. Thus, Magnusson et al. (2015, 2019) assess CO_2 savings from reusing and recycling ESR. Jain et al. (2020) compare LCA results of recycling and landfilling ESR for GWP and three other impact categories. Xu et al. (2022) conduct an environmental impact assessment for recycling ESR for GWP and three other impact categories along with energy consumption. Zhang et al. (2020) evaluate GWP from different ESR recycling and landfilling scenarios via LCA. Concerning DDS, Bates et al. (2015) apply LCA (not limited to GWP) to DDS management pathways including reuse and landfilling. Zhou et al. (2021) evaluate DDS recycling though LCA (for nine impact categories) and economic analysis. Finally, Svensson et al. (2022) and Ferrans et al. (2022) conduct both an LCA and a cost analysis of DDS for different management pathways including landfilling.

The review highlighted three information gaps in the existing scientific literature that are necessary to evaluate circular economy policy measures for CDW. First of all, the existing literature lacks detail on the environmental impacts of preparing for reuse and backfilling. Secondly, the literature lacks an analysis of the economic impacts of management pathways for excavated soils. Finally, no study has assessed the potential contribution of these two waste fractions to achieve the EU's Green Deal and circular economy objectives. To close these gaps, this study assesses the environmental and economic effects of ESR and DDS waste management in the EU using state-of-the-art datasets, with a focus on preparing for reuse and recycling.

2. Materials and methods

2.1. Quantification and characterization of waste

The main reference database to quantify the generation and treatment of ESR and DDS within the EU is Eurostat (database code *env_wasgt*). However, the definition and quantification of ESR and DDS is not treated homogenously among the EU countries, and thus waste generation data varies largely between EU counties. For that reason, the waste generation data of this study was further elaborated based on Damgaard et al. (2022), which improved Eurostat data with a literature search and country-specific data obtained through contacting stakeholders in relevant Member States. The new data quantifies non-hazardous ESR and DDS at EU level for 2020 at 444 Mt. and 79 Mt., respectively. The level of recycling and material recovery varies greatly across the EU, ranging from less than 10 % to almost 100 %, depending on the country (Cristóbal García et al., 2024).

Concerning treatment, this study used the reported data on Eurostat (database code *env_wastrt*) that are based on the treatment operations defined in the WFD and thus divided into recycling, recovery-backfilling, and disposal-landfill. Note that there is no specific data reported for preparing for reuse in the Eurostat data, even if the WFD recognises this category. The reported quantities are, on average in the EU, 35 % recycling, 40 % backfilling and 25 % landfilling for ESR, and 8 % recycling, 4 % backfilling and 88 % landfilling for DDS.

Finally, the composition (i.e., quality) of the waste is an important criterion for secondary material markets to be able to reduce the use of primary quarried materials. As mentioned before, there is no clear definition of ESR and DDS, neither in literature nor in legislation.

From the circular economy perspective, the most important features of ESR and DDS are the composition in terms of particle size distribution (i.e., % of clay, silt, sand, and coarse) and the soil organic carbon (SOC) content (in $g\ C\ kg^{-1}$ of soil). In this study, for ESR, the datasets available within the Land Use and Cover Survey (LUCAS) soil module were used (Orgiazzi et al., 2018). These include particle size distribution in the samples of topsoil (0–20 cm) for most of the EU members and are then extrapolated to the EU. Since no data is available for the subsoil, this data was considered as representative for the whole depth of the ESR. For DDS, there is no data at EU level of material composition that can differ from soils being usually dominated by silt and clay fractions (accounting for 60–90 % of the solid content). In this study, data from a case study in Sweden (Ferrans et al., 2019) was used to characterize DDS (further information for both fractions in the Supporting Material – section 1).

2.2. Impact assessment

LCA methodology was applied in accordance with ISO 14040/14044 standards. Complementary, LCC methodology presented in Martinez-Sanchez et al. (2015) was applied to perform both the environmental LCC (ELCC) and the full environmental LCC (feLCC), the former consisting of a financial assessment including already internalised environmental externalities (e.g., landfill and incineration tax) to which operators are subject, and the latter including costs for marketed goods along with the monetised environmental externalities (i.e., the effects on the welfare of the society caused by those; this is a partial social cost analysis as other social aspects are not addressed), expressed in shadow prices.

The Functional Unit (FU) was the management of one tonne of each individual fraction (i.e., ESR and DDS) from CDW and the general system boundaries of the study (see Fig. 1) were aligned with Caro et al. (2024) that included the generation stage (either excavation or dredging processes), the conditioning stage that accounts for all processes needed to adequate the wastes generated before the transport or the processing (e.g., dewatering processes for dredging spoils), the transport stage, and the processing stage (i.e., preparing for reuse, recycling and recovery operations and landfilling). Preparing for reuse, as well as recovery operations (i.e., backfilling) imply the collocation of the material at the receiving site to fulfil the expected function by means of machinery such as skid-steer loaders and compactors, and there is no difference between ESR and DDS. Concerning recycling operations, they consist of consecutive phases of several sieving, crushing, flocculation and drying processes, in order to produce individual materials (i.e., natural sand and natural clay) and these operations are the same for ESR and DDS. Finally, landfilling for both ESR and DDS is done considering an inert material landfill where leachate emissions are considered negligible. The inventory data needed for performing the LCA and LCC comprised data concerning technical parameters of the different management and treatment operations, as well as the consumption of energy, electricity, material, fuels and resources, and has been compiled through literature review and stakeholder consultation. For more information about the data used, see Supporting Material – section 2. Background data for modelling waste treatment technologies were taken from Ecoinvent centre 3.7.1 (Ecoinvent, 2023). The input-waste was assumed to carry no environmental burdens from the respective upstream life cycle stages, following the common “zero-burden” assumption applied in waste management LCA. The assessment was facilitated with the EASETECH software (Clavreul et al., 2014). To credit the reuse or recovery of materials via the alternative end-of-life management pathways, system expansion was applied as is common in waste management LCA (Ekvall, 2002) and in accordance with ISO 14040/14044 and the EU methods for Environmental Footprint (EF) (European Commission, 2021a).

2.3. Waste management pathways

The study assessed the four waste management pathways established in the waste hierarchy (see Table 1): 1) preparing for reuse (REU); 2) recycling (REC); 3) recovery-backfill (RCB); and 4) landfill (LAN). Note that for the modelling exercise, since backfilling must replace other materials that are not waste, the RCB option was modelled equal to REU for excavated soils, whenever they substitute the same material. In this case, the difference between the RCB and REU pathways is semantic, acknowledging that from the perspective of the waste hierarchy they are completely different options. ESR and DDS can be reused/recycled/recovered for several final applications and the secondary material obtained will substitute either natural aggregates (intended as sand, gravel, and sand and gravel mixture) or individual material fractions such as clay. It is important to quantify the amount of avoided raw material based on the substitutability factor accounting for the product quality and the market demand (Borghi et al., 2018). Further information on the substitutability factors used in this paper (also named replacement or substitution factors) can be found in the Supporting Material – section 3.

2.3.1. Life cycle impact assessment

This study includes 16 environmental impact categories that are currently recommended within the EF method, as implemented in the software EASETECH v3.4.0. Only results for Climate Change are presented in the main text of this article. Results for the remaining impact categories are reported in Cristóbal García et al. (2024). Also, economic impacts are assessed through ELCC that accounts for internal costs (annualised cost of capital along with operational expenditures and revenues) and internalised environmental taxes (i.e., already paid by companies) and through feLCC that includes internal costs (expressed as shadow prices, i.e., removing taxes and subsidies) summed up to external costs (also expressed as shadow prices; i.e., monetised environmental emissions to air, water, soil using de Bruyn et al. (2018)). The ELCC and feLCC results approximate the market effects of each scenario under the assumption that a well-functioning secondary materials market exists to facilitate transactions between buyers and sellers.

In the results, values above zero represent burdens or costs to society (environmental and economic, respectively), while values below zero represent savings or revenues to society (environmental and economic, respectively). The total net impact of the management of the waste at the level of individual pathways is calculated as the difference between the burdens/costs of the management pathway and the savings/revenues from the substituted products and co-products arising from that pathway. The “total” impact is thus a ‘net burden/cost’ when positive or a ‘net saving/revenue’ when negative (see Fig. 2).

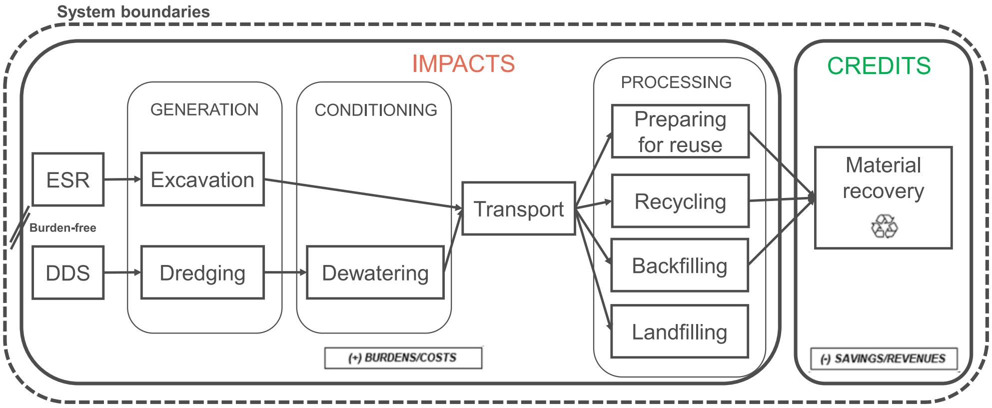

Fig. 1. System boundaries for the four waste management pathways. Impacts include burdens (LCA) and costs (LCC) coming from the waste management of each fraction; whereas, credits include savings (LCA) and revenues (LCC) from material recovery.

Table 1
Description of modelled waste management pathways for ESR and DDS with details of possible product substitution and substitutability factors (where applicable).

Fraction	Processing technology	Products/Outputs	Product substituted	Substitutability factor	Pathway code
Excavated soil and rocks (ESR)	Preparing for reuse Recovery - backfill	Soil	Natural aggregates	0.64	REU-RCB[(1)]
	Recycling	Individual components (sand, clay)	Natural sand Natural clay	1	REC
	Landfill	–	–	–	LAN
Dredging spoil (DDS)	Preparing for reuse	Dredged sediments	Natural aggregates	1	REU
	Recovery - backfill	Dredged sediments	Natural aggregates	0.75	RCB
	Recycling	Individual components (sand, clay)	Natural sand Natural clay	1	REC
	Landfill (Upland)	–	–	–	LAN

[1] The WFD defines that backfilling operations (RCB) must replace other materials that are not waste. Therefore, for excavated soils, backfill was modelled equal to preparing for reuse (Iacovidou et al., 2020).

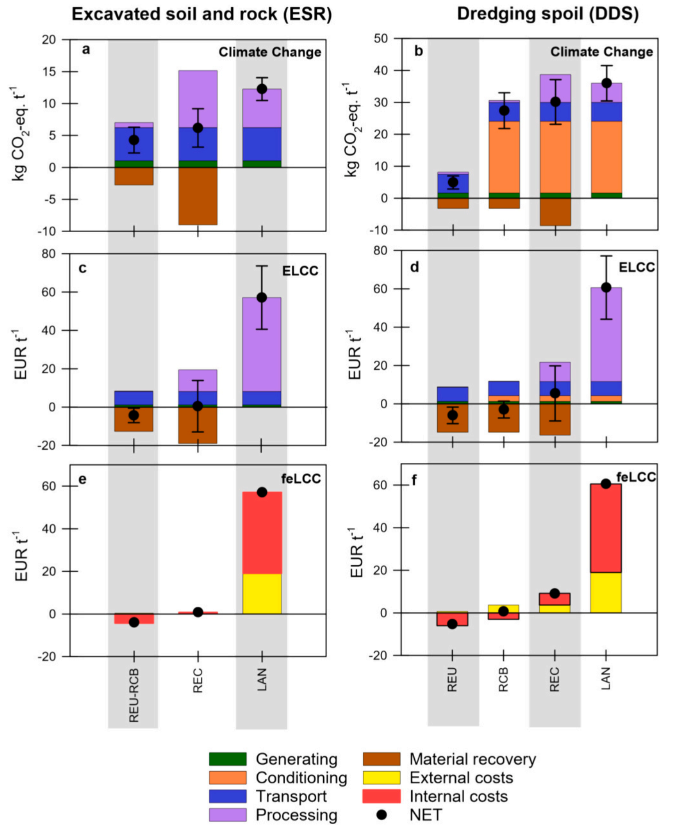

Fig. 2. LCA and LCC results per tonne of CDW fraction managed with breakdown of the contributions by process. The NET illustrates the sum of burdens and savings. REU - preparing for reuse; REC – recycling; RCB – recovery - backfilling; LAN – landfilling.

2.3.2. *Uncertainty analysis*

Parameter uncertainty was addressed using uncertainty propagation following the approach suggested in Bisinella et al. (2016). The total uncertainty of each parameter (i.e., of data points entering the model) considers both the uncertainty related to the intrinsic variation of the value and an additional uncertainty related to the quality of the data itself. The first is assigned to all parameters following a uniform distribution and the range assigned to the parameters is either based on literature, when available, or assumed to be +/− 20 %. The additional uncertainty on quality was quantified by means of the Pedigree Matrix using the approach suggested by Ciroth et al. (2016). For the Pedigree Matrix calculation, parameters were grouped in clusters and valued according to five indicators (further info on the Supporting Material – section 4). Finally, the uncertainty in the parameters is translated into a total parametrical variance per impact category that is given by the sum of the single parameter uncertainties (Bisinella et al., 2016).

2.4. *EU scenario-wide impacts*

This section aims to evaluate the possible contribution of ESR and DDS management to achieve the European Green Deal and the EU's circular economy objectives. Five scenarios were further assessed (see Table 2). These scenarios are combinations of the individual management pathways described earlier, either based on the *status quo*, technical feasibility or normative impositions. First, the baseline scenario (BSL) represents the *status quo,* the average management at EU level by 2020 according to Eurostat. The second and third scenarios explore the (technically feasible) maximum recycling potential (MRP) and maximum preparing for reuse potential (MPP) according to stakeholder consultations and data found in the reviewed literature (CityLoops, 2020). The fourth scenario represents the potential to include a legislative target on recycling (TRP) for those two fractions in line with the existing one on the WFD for CDW in general (at least 70 %) and focusing on recycling instead of backfilling as final disposition. The TRP scenario includes also a target on landfilling, limiting this management option to 10 % in line with the Landfill Directive. The fifth scenario, that builds on the TRP scenario, explores the potential of including a legislative target on preparing for reuse (TPP) in line with the EU taxonomy requirements for construction of new buildings where *at least 90 %* of the non-hazardous construction and demolition waste generated on the construction site shall be prepared for reuse or recycled, *excluding*

Table 2
Partitioning of the generated waste across management pathways for the five scenarios analysed.

Scenario	Management pathway	Fraction (%) [(1)]	
		ESR	DDS
Baseline (BSL)	REU	0	0
	REC	35	8
	RCB	40	4
	LAN	25	88
Maximum Recycling Potential (MRP)	REU	0	0
	REC	100	100
	RCB	0	0
	LAN	0	0
Maximum Preparing for reuse Potential (MPP)	REU	100	100
	REC	0	0
	RCB	0	0
	LAN	0	0
Target on Recycling Potential (TRP)	REU	0	0
	REC	70	70
	RCB	20	20
	LAN	10	10
Target on Preparing for reuse Potential (TPP)	REU	20	20
	REC	70	70
	RCB	0	0
	LAN	10	10

[1] The percentage reflects the share of the waste generated sent to the treatment (e.g., sent to recycling) and not what is considered reused or recycled in practice. However, losses and actual amount of recycled material were duly considered in the LCA calculation.

backfilling.

For the five scenario analyses, the material flow of each fraction (t $year^{-1}$) was multiplied by both the treatment share reported for them within each scenario and the environmental and economic impacts calculated for each management pathway. Results of this assessment are reported in net reduction of CO_2 eq. emissions and EUR savings (per year).

3. Results

3.1. Individual management pathways

For the Climate Change impact category, the waste hierarchy is respected for both ESR and DDS (see Fig. 2a and b, respectively). For the ESR, preparing for reuse (and in this case also backfilling) leads to a burden of 4 kg CO_2 eq. t^{-1} ± 2 and capitalizes in low processing impacts (mainly due to machine operations) and moderate savings from material recovery, followed by recycling with 6 kg CO_2 eq. t^{-1} ± 3 (mainly from the filter press operation), and finally landfilling with 12 kg CO_2 eq. t^{-1} ± 2. In the same line, for DDS, preparing for reuse leads to the lowest impact (5 kg CO_2 eq. t^{-1} ± 2), followed by backfilling (27 kg CO_2 eq. t^{-1} ± 6) and recycling (30 kg CO_2 eq. t^{-1} ± 7), and finally landfilling (36 kg CO_2 eq. t^{-1} ± 6). In this case, the main contributions to environmental impact are from the conditioning process (from dewatering), except for the preparing for reuse where the transport accounts for most of the impacts (since no dewatering is needed). The impacts on the other categories, except for Ozone Depletion, Land Use, and Resource Use, follow a similar trend to that of Climate Change with respect to the ranking of the scenarios and impact contributions (Cristóbal García et al., 2024).

The ELCC results are aligned with the LCA (see Fig. 2c and d for ESR and DDS, respectively). The scenario with the lowest cost for ESR is preparing for reuse (net revenue of EUR 4 t^{-1} ± 4) followed by recycling (net cost of EUR 0.5 t^{-1} ± 13, mainly due to filter press operation) and finally landfilling (net cost of EUR 57 t^{-1} ± 17). For DDS, the lowest cost is for preparing for reuse (net revenue of EUR 6 t^{-1} ± 4) followed by backfilling (net revenue of EUR 3 t^{-1} ± 4) and recycling (net cost of EUR 5 t^{-1} ± 14) and finally landfilling (net cost of EUR 61 t^{-1} ± 17). The main contributions to the costs of landfilling for both ESR and DDS are the processing (accounting for CAPEX and OPEX) as well as the landfill tax (at the EU average of EUR 19 t^{-1}).

Finally, the results from the feLCC (see Fig. 2e and f for ESR and DDS, respectively) follow a similar trend to that of the ELCC. Preparing for reuse is the best option, followed by recycling, and finally landfilling. External cost savings from material recovery are hindered by higher positive external costs from other processes (transport and processing) leading to a net positive external cost overall.

3.2. Scenario analysis

All scenarios (see Table 3) result in a net reduction of greenhouse gas (GHG) emissions and cost savings (per year) when compared to the baseline. The total costs are herein reported as savings because the cost of the baseline treatment pathway is avoided, which leads to financial savings and reduces societal costs when shifting from the baseline to the four different scenarios. As expected, the maximum potential scenarios show the highest savings and the highest GHG reduction potential. For the MPP, savings of up to EUR 7.6 billion $year^{-1}$ for ESR and EUR 4.7 billion $year^{-1}$ for DDS are foreseen with GHG reductions of 1.2 Mt. CO_2 eq. $year^{-1}$ and 2.4 Mt. CO_2 eq. $year^{-1}$, respectively. This represents a negative marginal abatement cost (i.e., opportunity to reduce emissions with a net economic gain) of 6.3 EUR kg^{-1} CO_2 eq., and 2 EUR kg^{-1} CO_2 eq., respectively. The MRP would also lead to high savings, EUR 5.4 billion $year^{-1}$ for ESR and EUR 3.8 billion $year^{-1}$ for DDS, and GHG reductions of 0.3 Mt. CO_2 eq. $year^{-1}$ and 0.4 Mt. CO_2 eq. $year^{-1}$, respectively. This represents again a negative marginal abatement cost of 16 EUR kg^{-1} CO_2 eq., and 9.5 EUR kg^{-1} CO_2 eq., respectively.

Concerning the possible targets, TRP and TPP show for ESR the same savings of EUR 3.3 billion $year^{-1}$ with GHG reductions of 0.2 Mt. CO_2 eq. $year^{-1}$, leading to a negative marginal abatement cost of 14 EUR kg^{-1} CO_2 eq. Note that the values do not change since preparing for reuse and backfilling of ESR is the same when substituting the same material. On the other hand, for DDS, TRP and TPP lead both to savings of EUR 3.5 billion $year^{-1}$ with GHG reductions of 0.4 Mt. CO_2 eq. $year^{-1}$ and 0.7 Mt. CO_2 eq. $year^{-1}$, i.e., negative marginal abatement costs of 9 EUR kg^{-1} CO_2 eq. and 5 EUR kg^{-1} CO_2 eq., respectively. Note that the auction price of carbon in the EU in 2023 averaged EUR 83 t^{-1}, and in 2024 averages EUR 58 t^{-1} at this writing (Eex, 2024).

4. Discussion

The EU Green Deal has recently recommended the intermediate target, before reaching the climate neutrality goal in 2050, of reducing GHG emissions by 90 % by 2040 relative to 1990. This would lead to an EU GHG budget based on equal per capita allocation of 16 Gt CO_2 for the period 2030–2050 and a net yearly GHG emissions by 2040 of 356 Mt. CO_2 eq. $year^{-1}$ (European Commission, 2024). GHG reduction potential from promoting preparing for reuse and recycling of ESR and DDS calculated in this study could contribute to relieve, depending upon the scenario, between 0.6 and 3.6 Mt. CO_2 eq. $year^{-1}$ (i.e., 0.2 % and 1 % of the net yearly GHG emissions foreseen). Furthermore, those reductions would come at a potential net savings, between EUR 6.8 and 12.3 billion $year^{-1}$, comparing to business-as-usual. It should be noted that such potential economic savings are estimated under specific assumptions, which may change according to the local conditions and markets involved.

The regulatory framework could do more to foster the environmentally sound management of ESR and DDS waste (and in general all CDW waste fractions), to reach the full potential contribution of ESR and DDS towards the transition to the circular economy. Indeed, the issue highlighted in this study is not just restricted to the quantity of waste that needs to be managed, along with the associated impacts, but also to the huge loss of resources within the economy, in terms of materials and ecosystem services. As an example, the 444 Mt. of ESR reported as waste in 2020 in the EU, that are mostly clean, fertile and healthy and could be safely reused according to the European Commission (2021b), would represent 185,000 ha (assuming that the top soil layer is of 20 cm and presents an average density of 1.2 g cm^{-3}), similar to the area of London (UK) or 0.12 % of the total agricultural land in the EU. Additionally, taking into account both the average values SOC from the LUCAS soil database (46.2 g of C kg^{-1} of soil) (see Table A1 in Supporting Material –

Table 3
Total annual GHG emission reduction and total annual cost for the four scenarios analysed by waste fraction - Maximum Recycling Potential (MRP), Maximum Preparing for reuse Potential (MPP), Target on Recycling Potential (TRP), Target on Preparing for reuse Potential (TPP).

Scenario	MRP		MPP		TRP		TPP	
Fraction	Total GHG reduction (Mt. CO_2 eq. $year^{-1}$)	Total Cost saving (billion EUR $year^{-1}$)	Total GHG reduction (Mt. CO_2 eq. $year^{-1}$)	Total Cost saving (billion EUR $year^{-1}$)	Total GHG reduction (Mt. CO_2 eq. $year^{-1}$)	Total Cost saving (billion EUR $year^{-1}$)	Total GHG reduction (Mt. CO_2 eq. $year^{-1}$)	Total Cost saving (billion EUR $year^{-1}$)
ESR	0.3	5.4	1.2	7.6	0.2	3.3	0.2	3.3
DDS	0.4	3.8	2.4	4.7	0.4	3.5	0.7	3.5

section 1), removed SOC stocks could be around 21 Mt. C (range from 7 to 56 Mt. C) per year affecting directly on soil fertility and food production.

4.1. Barriers to transition to more circular and better performing management options for ESR and DDS

The barriers to preparing for reuse and recycling are complex because they are related to different aspects of regulation, reporting, and market inefficiencies.

There is a need for common policies and clear definitions for ESR and DDS at EU level since they are not applied homogenously from a legal perspective. Establishing End-of-Waste criteria for inert waste may also be a means to facilitate reuse and recycling by constructors/producers, once it is clear that a market demand exists.

Concerning the reporting of data, a clear guidance for national data collection is needed due to the complete lack of statistical data for the category of preparing for reuse. This has been highlighted within the EU soil strategy for 2030 (European Commission, 2021b) that promotes the investigation of the streams of ESR generated, treated and reused in the EU, and benchmark the market situation in Member States to give a complete picture of the situation in the EU.

There is need for more coordination and information exchange concerning quantities and qualities of materials between value chain actors. The upcoming Soil Monitoring Law will tackle the need and potential for a legally binding 'passport for excavated soil' addressing this barrier.

From an economic point of view, several factors hamper the development of circular management pathways (Cristóbal García et al., 2024). For example, although most countries have landfill taxes (and/or gate fees/tipping fees), they might be not high enough to dissuade landfilling, thus this option often remains at a lower cost compared to recycling, leading to a lack of economic incentives for companies to invest in preparing for reuse and recycling. Also, the competition from newly quarried materials at lower or comparable market prices compared with recycled materials hampers demand.

Stakeholder consultation and review of proposed policies to address the abovementioned barriers is an important part of any review of regulatory frameworks.

5. Conclusions

According to the latest data available, ESR and DDS are still landfilled to a great extent (i.e., 25 % and 88 %, respectively). This disposal option represents a loss of economic value and resources since that material, when prepared for reuse, recycled and, to some extent backfilled, could enter again into the construction material market and serve as a substitute for the use of virgin material. In the case of recycling, individual material streams such as natural sand or natural clay can be substituted with recycled ESR and DDS. Overcoming the actual barriers to circular management, towards "higher" outcomes of the Waste Framework Directive's waste hierarchy than disposal in landfill is critical to foster the market for secondary raw materials in the construction sector, thus reducing primary resource extraction and the environmental impacts associated with inefficient resource use.

This article questions if different regulation-driven policy scenarios would result in better environmental and economic outcomes for ESR and DDS than current practice. Results show that promoting preparing for reuse and recycling of ERS and DDS in line with the waste hierarchy, could make non-negligible contributions to yearly GHG reductions and possibly economic savings (i.e., up to 3.6 Mt. CO_2 eq. year^{-1} and EUR 12.3 billion year^{-1}, respectively; costs estimates are uncertain and are anticipated to vary according to local factors).

Although the current contribution addresses many scientific gaps through LCA, ERS and DDS and their potential uses and costs are still poorly understood. It is important to highlight that innovative uses of ERS and DDS such as constructed technosols (i.e., artificial soils that can be used for agriculture) and energy storage batteries using excavated material (e.g., EU project NewSETS) must be further investigated since they could be new markets.

Finally, the potential speed of commercialisation of new management practices and the corresponding timing of climate change mitigation benefits is not well understood. In addition to practical research, the authors suggest additional consultation with stakeholders and the construction industry to plan the future sustainable and circular use of ERS and DDS.

CRediT authorship contribution statement

Jorge Cristóbal: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gillian Foster:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Dario Caro:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Felipe Yunta:** Writing – review & editing, Writing – original draft, Formal analysis. **Simone Manfredi:** Writing – review & editing, Supervision, Project administration. **Davide Tonini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank all stakeholders who have contributed to the assumptions and supplied primary data for the LCA.

Disclaimer

The views expressed in the article are the sole responsibility of the authors and in no way represent the view of the European Commission and its services.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173859.

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