detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CHARACTERISTICS OF RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE ACCORDING TO THE ITALIAN EoW REGULATION

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Article Info:
Received:
5 October 2025
Revised:
16 December 2025
Accepted:
16 January 2026
Available online:
8 February 2026

Keywords:
Construction and Demolition Waste
Recycled aggregates
Waste recovery
Leaching behaviour

ABSTRACT
Construction and Demolition Waste (CDW) accounts for approximately one-third of the industrial waste generated in the European Union, posing significant environmental challenges. The building sector may significantly increase sustainability through effective CDW management and the production of good quality recycled aggregates (RAs). The construction sector is one of the main sectors involved in achieving environmental sustainability through the application of circular economy principles. In Europe, CDW recovery rates generally exceed regulatory target; only few countries don't reach 70% recovery by weight outlined in Directive 2008/98/EC. ISPRA (Italian Institute for Environmental Protection and Research) data shows that the CDW recovery rate in Italy is over 81%. However, diverging perspectives exist; reports shows illegal CDW dumping in some Regions, compromising environmental and public health efforts. Despite progress, RAs still present challenges, mostly because of its heterogeneity. To safeguard the recovery, the End-of-Waste regulation for inert waste was introduced in Italy: the requirements introduced by Ministerial Decree 152/2022, replaced by the Ministerial Decree n.127/2024, could involve several issues to promote the CDW recovery. The aim of this study is to illustrate the characteristics of RAs with respect to the requirements set by the EoW regulation, in order to evaluate the effect of its implementation on the recovery feasibility. About 2500 laboratory certificates (chemical analysis and leaching tests) are collected; they referred to CDW and RAs quality monitoring in 2020-2022 carried out by 28 Italian recycling plants. These data were analyzed in order to statistically verify the compliance of RAs with the EoW requirements.

1. INTRODUCTION

The "linear" economy, also known as the "take-make-dispose" model, has been the dominant industrial system for the past 150 years. It involves extracting raw materials, mass consumption, and producing waste once the product's life cycle has ended. This approach is recognized as unsustainable and it is necessary to adopt a new "circular" economy model that reduces and eliminates waste, diversifies material sources, and extends the life of products (Papadaki at al., 2022).

The Community regulatory framework focuses on the recovery and use of waste materials to preserve natural resources through the Waste Framework Directive 2008/98/EC and its amendment EU Directive 2018/851. The European Commission's action plan prioritizes seven crucial sectors for a circular economy, including buildings, plastics, textiles, electronic waste, food and water, packaging, batteries and vehicles.

The building sector is a major contributor to the depletion of natural resources due to its intensive use. Construction and demolition waste (CDW), listed in Chapter 17 of the European Waste List (EWC), is one of the largest waste streams produced in Italy and Europe. In 2023, Italy produced over 61 million tonnes of CDW (ISPRA, 2025), excluding excavated soil and rock, and dredging spoil. It represents the fourth largest producer in Europe after Germany, France, and the United Kingdom (Eurostat, 2022).

The Italian CDW recovery rate in 2023 was 81% (ISPRA, 2025), exceeding the 70% goal established by European Directive 2008/98/EC. Countries with high recovery rates are the ones with the best practices in terms of waste treatment. For example, in the Netherlands, Luxembourg and Belgium, characterized by densely populated areas,

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https://doi.org/10.31025/2611-4135/2026.19564

great efforts have been made to reduce the disposal of mineral waste from construction and demolition. Many of the Member States with higher recovery rates have a good range of CDW management structures, such as Denmark, Italy, Ireland, Germany and Luxembourg (European Commission, 2017).

To do this, it is very important to know their composition, that is influenced by several factors, including the variability of raw materials, the construction practices, the demolition techniques (usually non-selective mode is adopted), and the lack of advanced treatment processes in recycling plants (Juenger and Siddique, 2015; Silva et al., 2017; Gálvez-Martos et al., 2018; Ruggeri et al., 2019).

The heterogeneous mixture of CDW components (Bianchini et al., 2020; Diotti et al., 2021) makes it difficult to recycle and market recycled aggregates (RAs) from their treatment. In fact, according to Caro et al. (2024), the average CDW in the EU has a high mixed fraction composition (59.2%). The individual fractions composing CDW are: concrete (24%), bricks (5%), metals (4.3%), wood (2.3%), hazardous components (1.8%), gypsum (1.4%), ceramics and tiles (1.2%), insulation materials (0.3%), plastic (0.2%), glass (0.2%), paper and cardboard (0.2%).

The chemical composition of RAs depends on the characteristics of the CDW from which they originate (Butera et al., 2014). Because CDW undergoes simple mechanical treatment, its elements often remain in RAs. Literature shows chromium as one of the most critical compounds. Total chromium, a major concrete component, can appear in high concentrations due to raw materials (Sinyoung et al., 2011; Estokova et al., 2018), but it also derives from ceramic and asphalt fractions. Zinc, vanadium, and nickel are also found, especially in cementitious and bituminous materials, with vanadium common in bitumen. Ceramic, clay, and brick fractions show high sulphate and fluoride levels, particularly in pure gypsum, with very high concentrations (Cilli et al., 2017; Imteaz et al., 2020). Bituminous mixtures contain significant hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), mainly from traffic-related activities (Sadler et al., 1999).

In Italy, the recycled aggregates (RAs) from CDW treatment are mainly used for infrastructure construction (roads, railways, cycle paths, etc.) (81.2%), followed by fillings and other uses (11.6%). The using of RAs for non-structural concrete (6.8%), and structural concrete (0.4%) production is still very low. This is due to the low in-situ generation of RAs derived from concrete demolition only (EWC 170101), that can be used, according to regulations, for new concrete production (Fondazione per lo sviluppo sostenibile and FISE UNICIRCULAR, 2021).

To promote the shifting to a circular economy, the EU has established that waste status ends when a material is subjected to recovery processes in accordance with specific requirements. Currently, End-of-Waste (EoW) criteria have been defined, at European level, for the following categories of waste: scrap iron, steel and aluminium, glass cullet, and copper scrap. In Italy, according to the requirements reported in Legislative Decree 152/2006 (Italian Government, 2006) and subsequent amendments (article 184-ter), EoW regulations are available for the following waste categories: bituminous conglomerate, absorbent hygiene personal care products, SRF (Solid Recovered Fuel), End-of-Life Tires (ELT) derived rubber, paper and board, CDW. Additionally, EoW regulations are being drafted for road sweeping waste, textile waste, bituminous membrane, and gypsum-based waste.

As concerns CDW, EoW criteria have not yet been defined at European level, although some projects are available and a preliminary list of pre-selected CDW and by-product streams is investigated (Reetsch et al., 2024). The JRC has published a draft technical proposal on EoW criteria for mineral CDW, which will then be used as a basis by the European Commission for defining the relevant Regulation (Egle et al., 2025). Similar to Austria, France, the Netherlands, Belgium, the United Kingdom and Ireland, recently the EoW regulation for inert waste has been also published in Italy. Other countries (Denmark, Finland, Czech Republic, Germany, Spain and Sweden) that don't have the EoW criteria have nevertheless adopted leaching criteria following European standards (Velzeboer and van Zomeren, 2017).

An analysis of End of Waste (EoW) criteria across European countries shows differences in accepted input waste, though CDW—cement/concrete, bricks, tiles, and ceramics—is universally considered a basic material for recovery and RAs production. The Netherlands applies EoW rules for "stony waste" from construction, renovation, and demolition, limiting codes to EWC 17 01 01 (concrete), 17 01 02 (bricks), and 17 01 07 (mixtures). Belgium (Wallonia) only accepts chapter 17 codes, unlike Italy, which also allows others; Ireland permits a broad range, while France is very selective.

For RAs composition, Dutch limits for parameters like sum of PAHs and PCBs are less strict than Italy's. France allows concrete and mixed aggregates under limits for hydrocarbons (C10-C21), PAHs, TOC, and BTEX, generally higher than Italian criteria. Regarding pollutant release, leaching tests are different: e.g. Austria uses EN 12457-4 (10 L/kg liquid-to-solid ratio, 10 mm max size vs. Italy's 4 mm), while the Netherlands adopts EN 14405 up-flow percolation. Detected parameters also vary; Austria sets fewer limits. Overall, Italian values are among the most restrictive (Velzeboer and van Zomeren, 2017).

The first version of Italian EoW regulation published in 2022 (Ministerial Decree 152/2022, Italian Ministry of ecological transition, 2022) has raised some concerns in the construction and recycling sector, with the risk to increase the amount of CDW sent to landfills. It has been noted that it is challenging to comply with the EoW criteria, particularly those pertaining to the content of pollutants in the solid matrix that set (in 2022 release) the same (and very low) limit values for all applications of RAs derived from CDW treatment.

In 2024 the Ministerial Decree n. 127/2024 (Italian Ministry of environment and energy security, 2024) replaced the first EoW version, and some changes were implemented, in order to make its application more effective to move towards a circular economy approach. The addition of various threshold limits for the content of pollutants dependent on the types of RA use was the primary change with regard to the 2022 version.

This work aims to highlight the chemical and environmental characteristics of CDW and RAs obtained from their treatment and to compare them with the EoW criteria outlined in the recent Italian regulation. The statistical results presented are based on the elaboration of 2500 certificates of analysis obtained from 28 Italian CDW recycling plants.

2. MATERIALS AND METHODS

2.1 Data collected

Thanks to the collaboration with the National Association of Building Constructors (ANCE), the Italian CDW treatment facilities were contacted to carry out a survey using a questionnaire. This survey's objectives are to examine the kinds of treatments used in recycling facilities, the quantity and kind of CDW that are treated, the production of RAs, the internal quality control procedures for incoming waste and outgoing aggregates, and to gather historical information regarding the qualitative features of the treated CDW and the RA generated.

28 CDW recycling plants took part to the survey and provided the required data. The location of these plants is reported in Figure 1. It can be noted that the medium- and high-capacity plants (with CDW amount higher than 100 kt/year) account for about 40%.

The plants considered have been also classified by EWC codes of the waste they can receive. As shown in Figure 2, the most commonly treated waste is mixed fraction (EWC 17 09 04), followed by soil and rock (EWC 17 05 04), and concrete (EWC 17 01 01).

These plants provided 2500 certificates of analysis both on CDW and RAs referred to the period 2020-2022. Table 1 shows the number of available certificates divided according to the type of treated waste. The analyses include the determination of chemical composition (to measure the content of pollutants in the solid matrix) and leaching test in water carried out with a liquid-to-solid ratio of 10 L/kg, according to UNI EN 12457-2 (the leaching test with CO_2 saturated water is applied only to the samples of the plants located in Bolzano Province).

It is evident that around 70% of CDW certificates, including those pertaining to leaching tests and chemical composition, make reference to mixed waste (EWC 17 09 04). Regarding RAs, it is frequently impossible to know the type of CDW from which they were obtained (in 60% of cases for chemical composition and 74% for leaching test).

Although the number of tests available for CDW (1155) and RAs (1337) is similar, there are more chemical composition measurements available for CDW (77%) and more leaching test results for RAs (71%).

2.2 Elaboration criteria

As concerns graphical representation, the box-plot methodology was applied. This methodology allows evaluating the entirety of the data distribution in relation to

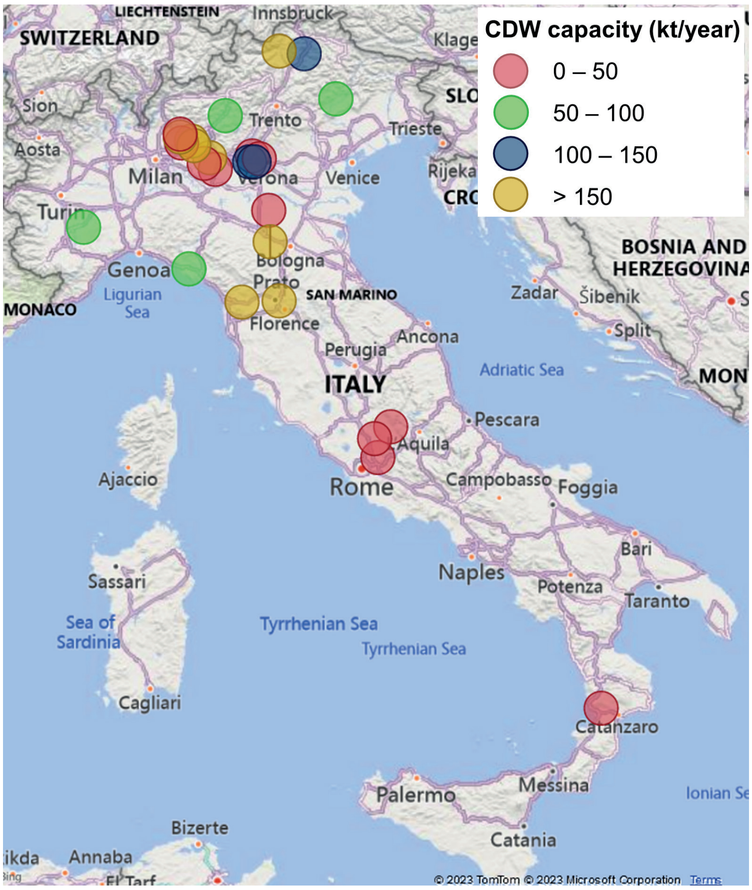

FIGURE 1: CDW treatment plants that took part in the survey: location and size category.

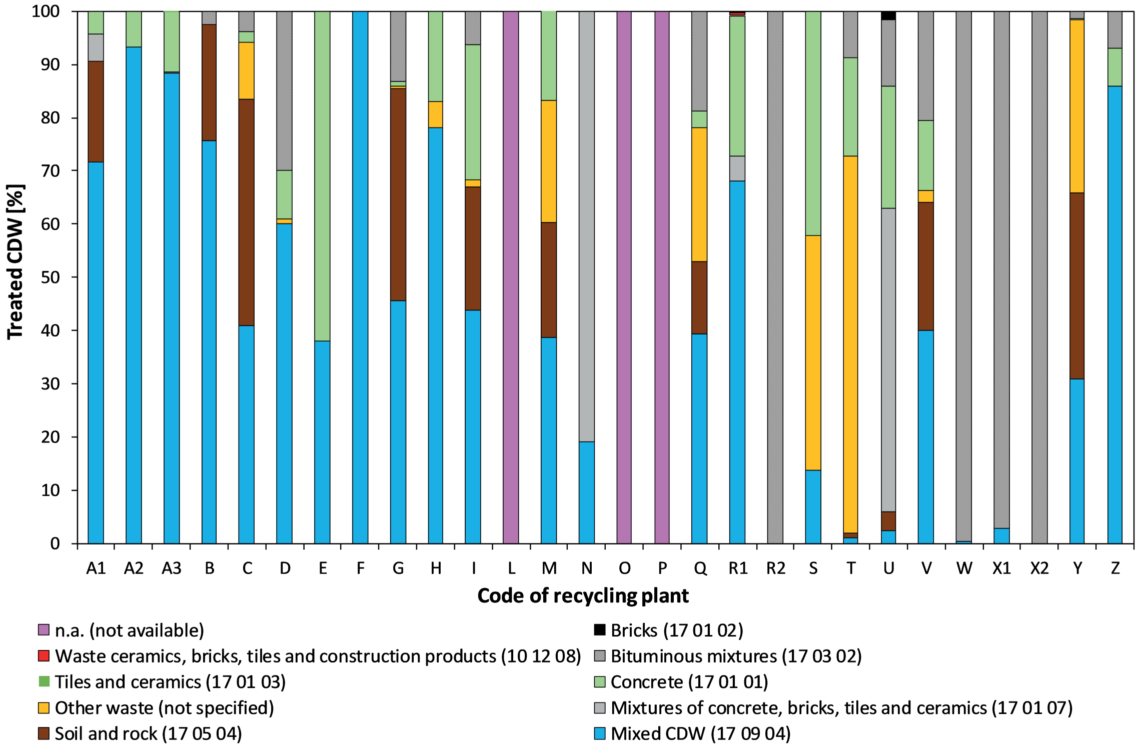

FIGURE 2: Distribution of treated CDW by EWC code (reference year: 2022).

specific statistical values including the 25th, 50th, and 75th percentiles. The basic idea is to identify the central observations with a "box" the central observations, with "tails" coming out of the box the values that are closest to the box, and with dots and stars the anomalous observations. A box plot represents the distribution of data and consists of a box from the first quartile (Q1) to the third quartile (Q3). The median of the data is represented by a horizontal line inside the box (Q2). Approximately 50% of the data falls within the box (IQR, calculated as the difference between Q3 and Q1).

The tails of the distribution, which are the extreme values, are represented by continuous lines starting from the edges of the box (Q1 and Q3) and ending with two other horizontal lines, the whiskers. The tails delimit the intervals (1.5 IQR) in which the lower values of Q1 and the higher values of Q3 are located. The limit values for the whiskers are defined as Q1 - 1.5 * IQR for the lower whisker and Q3 + 1.5 * IQR for the upper whisker. The values outside the tails are considered anomalous values and significantly deviate from the other data points in the same population. Outliers (between 1.5 and 3 times IQR) are considered normal while extreme values (over 3 IQR) are generally rare and far from the central data distribution represented by the box.

The results are also summarized in tables. For each parameter reported in the laboratory certificates, the minimum, maximum, and average values were given. The results obtained were compared with the following limit values:

- For the content of pollutants in RAs (chemical composition), the limit values set by the EoW regulation (Ministerial Decree n. 127/2024 - Annex 1, Table 2), which provides two different columns:
  - the column 1 - more restrictive limits - for the use of RAs in environmental reclamation and filling;
  - the column 2 - less restrictive limits - for other application of RAs such as bituminous mixtures, foun-

TABLE 1: Number of certificates of analysis available for CDW and RAs.

Type of waste (EWC)	Construction and demolition waste (CDW)		Recycled aggregates (RAs)	
	Chemical composition	Leaching test	Chemical composition	Leaching test
Concrete (17 01 01)	8	21	0	38
Mixtures of concrete, bricks, tiles and ceramics (17 01 07)	31	11	0	0
Bituminous mixtures (17 03 02)	102	47	72	232
Soil and rock (17 05 04)	74	34	10	18
Mixed CDW (17 09 04)	461	331	0	7
Other waste / not available	17	18	119	841
Total	693	462	201	1136

dation layer and sub-bases for roads, and concrete production.

- For the release of pollutants from RAs (results of leaching test):
  - the limit values established by EoW regulation (Ministerial Decree n. 127/2024 - Annex 1, Table 3);
  - the limit values set by Ministerial Decree n. 186/2006 for the waste recovery in simplified procedure (the limits are equal to the ones imposed by EoW regulation, with the exception of sulphates and chlorides).

In these tables, the results obtained are also reported in terms of percentages of exceeding (or compliance). In many cases, especially for the chemical composition, the instrumental determination value (detection limit - D.L.) reported in analytical certificates was higher than the threshold value (especially for the more restrictive limits). Therefore, the following percentages were calculated:

- certain exceedance: number of samples that certainly exceed the limit (e.g. CrVI = 2.47 mg/kg greater than the limit of 2 mg/kg), in relation to the total number of data available;
- possible exceedance: number of samples that could exceed the limit, taking into account only the values reported as < D.L., when D.L. is greater than the limit itself (example CrVI < 5 mg/kg compared to the limit of 2 mg/kg), in relation to the total number of data available;
- certain and possible exceedance: number of samples

TABLE 2A: Chemical composition of RAs and compliance/non-compliance with the more restrictive requirements provided by Italian EoW regulation.

Parameter		Number of data	Content			(A) Tab.2, Col. 1, Ministerial Decree 127/2024				
			Minimum	Average	Maximum	Limit values	Non-compliance			Certain compliance
							Certain	Possible	Certain and possible	
Chromium VI	[mg/kg$_{DM}$]	131	<0.1	0.27	<5	2	0.8%	1,5%	2.3%	97.7%
Benzene	[mg/kg$_{DM}$]	31	<0.002	0.20	<1	0.1	0.0%	32.3%	32.3%	67.7%
Ethylbenzene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	0.5	0.0%	6.5%	6.5%	93.5%
Styrene	[mg/kg$_{DM}$]	23	<0.002	0.12	<1	0.5	0.0%	8.7%	8.7%	91.3%
Toluene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	0.5	0.0%	6.5%	6.5%	93.5%
Xylene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	0.5	0.0%	6.5%	6.5%	93.5%
BTEXS	[mg/kg$_{DM}$]	25	<0.05	0.20	<0.5	1	0.0%	0.0%	0.0%	100.0%
Benzo(a)anthracene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	0.5	2.0%	42.9%	44.9%	55.1%
Benzo(a)pyrene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	0.1	5.1%	78.6%	83.7%	16.3%
Benzo(b)fluoranthene	[mg/kg$_{DM}$]	98	<0.005	4.51	<10	0.5	0.0%	42.9%	42.9%	57.1%
Benzo(k)fluoranthene	[mg/kg$_{DM}$]	73	<0.003	4.47	<10	0.5	0.0%	46.6%	46.6%	53.4%
Benzo(g.h.i)perylene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	0.1	5.1%	77.6%	82.7%	17.3%
Chrysene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	5	0.0%	41.8%	41.8%	58.2%
Dibenzo(a.e)pyrene	[mg/kg$_{DM}$]	96	<0.002	4.50	<10	0.1	0.0%	78.1%	78.1%	21.9%
Dibenzo(a.l)pyrene	[mg/kg$_{DM}$]	95	<0.002	4.54	<10	0.1	0.0%	77.9%	77.9%	22.1%
Dibenzo(a.i)pyrene	[mg/kg$_{DM}$]	98	<0.002	4.43	<10	0.1	0.0%	78.6%	78.6%	21.4%
Dibenzo(a.h)pyrene	[mg/kg$_{DM}$]	98	<0.002	4.43	<10	0.1	1.0%	78.6%	79.6%	20.4%
Dibenzo(a.h)anthracene	[mg/kg$_{DM}$]	88	<0.002	4.88	<10	0.1	1.1%	76.1%	77.3%	22.7%
Indenopyrene	[mg/kg$_{DM}$]	87	<0.004	4.97	<10	0.1	0.0%	74.7%	74.7%	25.3%
Pyrene	[mg/kg$_{DM}$]	86	<0.005	4.98	<10	5	0.0%	47.7%	47.7%	52.3%
Sum of PAH	[mg/kg$_{DM}$]	88	<0.005	12.85	<70	10	0.0%	11.4%	11.4%	88.6%
Phenol	[mg/kg$_{DM}$]	19	<0.0025	0.12	<1	1	0.0%	0.0%	0.0%	100.0%
PCB	[mg/kg$_{DM}$]	19	<0.001	0.11	<1	0.06	5.3%	10.5%	15.8%	84.2%
Heavy hydrocarbons (C>12)	[mg/kg$_{DM}$]	81	<20	361	9464	50	22.2%	0.0%	22.2%	77.8%
Asbestos	[mg/kg$_{DM}$]	197	Absent	63	<1000	100	0.0%	2.0%	2.0%	98.0%
Floating materials	[cm^3/kg]	6	0.01	0.01	0.01	5	0.0%	0.0%	0.0%	100.0%
Extraneous material	[%]	6	<0.01	0.34	<1	1	0.0%	0.0%	0.0%	100.0%

(A): use of RAs for environmental reclamation and filling

PAH: polycyclic aromatic hydrocarbons; PCB: polychlorinated biphenyls; BTEXS: sum of benzene, toluene, ethylbenzene, xylene, and styrene

TABLE 2B: Chemical composition of RAs and compliance/non-compliance with the less restrictive requirements provided by Italian EoW regulation.

Parameter		Number of data	Content			(B) Tab.2, Col. 2, Ministerial Decree 127/2024				
			Minimum	Average	Maxi-mum	Limit values	Non-compliance			Certain compli-ance
							Certain	Possible	Certain and possible	
Chromium VI	[mg/kg$_{DM}$]	131	<0.1	0.27	<5	15	0.0%	0.0%	0.0%	100.0%
Benzene	[mg/kg$_{DM}$]	31	<0.002	0.20	<1	2	0.0%	0.0%	0.0%	100.0%
Ethylbenzene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	50	0.0%	0.0%	0.0%	100.0%
Styrene	[mg/kg$_{DM}$]	23	<0.002	0.12	<1	50	0.0%	0.0%	0.0%	100.0%
Toluene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	50	0.0%	0.0%	0.0%	100.0%
Xylene	[mg/kg$_{DM}$]	31	<0.002	0.22	<1	50	0.0%	0.0%	0.0%	100.0%
BTEXS	[mg/kg$_{DM}$]	25	<0.05	0.20	<0.5	100	0.0%	0.0%	0.0%	100.0%
Benzo(a)anthracene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	10	0.0%	0.0%	0.0%	100.0%
Benzo(a)pyrene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	10	0.0%	0.0%	0.0%	100.0%
Benzo(b)fluoranthene	[mg/kg$_{DM}$]	98	<0.005	4.51	<10	10	0.0%	0.0%	0.0%	100.0%
Benzo(k)fluoranthene	[mg/kg$_{DM}$]	73	<0.003	4.47	<10	10	0.0%	0.0%	0.0%	100.0%
Benzo(g.h.i)perylene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	10	0.0%	0.0%	0.0%	100.0%
Chrysene	[mg/kg$_{DM}$]	98	<0.005	4.44	<10	50	0.0%	0.0%	0.0%	100.0%
Dibenzo(a.e)pyrene	[mg/kg$_{DM}$]	96	<0.002	4.50	<10	10	0.0%	0.0%	0.0%	100.0%
Dibenzo(a.l)pyrene	[mg/kg$_{DM}$]	95	<0.002	4.54	<10	10	0.0%	0.0%	0.0%	100.0%
Dibenzo(a.i)pyrene	[mg/kg$_{DM}$]	98	<0.002	4.43	<10	10	0.0%	0.0%	0.0%	100.0%
Dibenzo(a.h)pyrene	[mg/kg$_{DM}$]	98	<0.002	4.43	<10	10	0.0%	0.0%	0.0%	100.0%
Dibenzo(a.h)anthracene	[mg/kg$_{DM}$]	88	<0.002	4.88	<10	10	0.0%	0.0%	0.0%	100.0%
Indenopyrene	[mg/kg$_{DM}$]	87	<0.004	4.97	<10	5	0.0%	47.1%	47.1%	52.9%
Pyrene	[mg/kg$_{DM}$]	86	<0.005	4.98	<10	50	0.0%	0.0%	0.0%	100.0%
Sum of PAH	[mg/kg$_{DM}$]	88	<0.005	12.85	<70	100	0.0%	0.0%	0.0%	100.0%
Phenol	[mg/kg$_{DM}$]	19	<0.0025	0.12	<1	60	0.0%	0.0%	0.0%	100.0%
PCB	[mg/kg$_{DM}$]	19	<0.001	0.11	<1	5	0.0%	0.0%	0.0%	100.0%
Heavy hydrocarbons (C>12)	[mg/kg$_{DM}$]	81	<20	361	9464	750	11.1%	0.0%	11.1%	88.9%
Asbestos	[mg/kg$_{DM}$]	197	Absent	63	<1000	100	0.0%	2.0%	2.0%	98.0%
Floating materials	[cm^3/kg]	6	0.01	0.01	0.01	5	0.0%	0.0%	0.0%	100.0%
Extraneous material	[%]	6	<0.01	0.34	<1	1	0.0%	0.0%	0.0%	100%

(B): use of RAs for bituminous mixtures, foundation layer and sub-bases for roads, railways, airports and civil/industrial yards, concrete production.

PAH: polycyclic aromatic hydrocarbons; PCB: polychlorinated biphenyls; BTEXS: sum of benzene, toluene, ethylbenzene, xylene, and styrene ; DM: dry matter

that could exceed the limit, considering not only the certain exceedances (e.g. CrVI = 2.47 mg/kg greater than the limit of 2 mg/kg), but also values reported as < D.L., where D.L. exceeds the limit itself (example CrVI < 5 mg/kg compared to the limit of 2 mg/kg), in relation to the total number of data available;

- certain compliance: the number of samples that with certainty comply with the regulatory limit, in relation to the total number of available data.

3. RESULTS

3.1 Chemical composition of recycled aggregates

In this paragraph, the results about RAs chemical composition are shown. In Tables 2A and 2B, the non-compliance values are highlighted in grey cell. Moreover, the miniminum, average, and maximum contents of pollutants are reported (the average values are calculated considered the values lower than detection limit (D.L.) equal to D.L.).

Heavy hydrocarbons (C>12) are the most critical pollutants: it can be note (Table 2A) that 22% of the analyzed samples don't respect (certainly) the more restrictive limit (reported on EoW regulation – Ministerial Decree 127/2024, Table 2, column 1 – that regulates the use of RAs for environmental reclamation and filling). Benzo(a) pyrene, benzo(g,h,i)perylene, and PCB (polychlorinated biphenyls) show certain exceedances of about 5% with respect the more restrictive limit values. Despite this percentage be quite low, the possible non-compliance is high (also up to 79%) for several PAHs and benzene. Based on

TABLE 3: Results of leaching tests on RAs and non-compliance with requirements provided by the Italian EoW regulation (M.D. 127/2024) and the Italian waste recovery legislation (M.D. 186/2006).

Parameter		Number of data*	Minimum	Average	Median	Maximum	Ministerial Decree 127/2024, Tab. 3		Ministerial Decree 186/2006, Annex 3	
							Limit values	Non-compliance	Limit values	Non-compliance
pH	[-]	998	6.4	10.1	10.0	12.6	5.5-12	0.4%	5.5-12	0.4%
Nitrates	[mg/L]	1009	<0.1	11.4	5.0	155	50	0.4%	50	0.4%
Fluorides	[mg/L]	1009	<0.025	0.41	0.25	33.3	1.5	0.3%	1.5	0.3%
Sulphates	[mg/L]	1009	<1	55.5	29.2	816	750	0.2%	250	0.8%
Chlorides	[mg/L]	1009	0.55	11.1	10.0	89.0	750	0.0%	100	0.0%
Cyanide	[µg/L]	1007	<0.01	8.78	10.0	<50	50	0.0%	50	0.0%
Barium	[mg/L]	1009	<0.0001	0.07	0.09	<5	1	0.2%	1	0.2%
Copper	[mg/L]	1009	<0.0001	0.01	0.01	0.08	0.05	0.2%	0.05	0.2%
Zinc	[mg/L]	1009	<0.0001	0.07	0.05	4	3	0.1%	3	0.1%
Beryllium	[µg/L]	1009	<0.001	1.17	1.00	9.10	10	0.0%	10	0.0%
Cobalt	[µg/L]	1009	<0.005	3.91	5.00	28.8	250	0.0%	250	0.0%
Nickel	[µg/L]	1009	<0.0001	2.34	1.00	15.9	10	0.2%	10	0.2%
Vanadium	[µg/L]	1009	<0.01	15.3	10.7	211	250	0.0%	250	0.0%
Arsenic	[µg/L]	1007	<0.001	3.91	3.60	33.1	50	0.0%	50	0.0%
Cadmium	[µg/L]	1008	<0.001	0.57	0.50	<5	5	0.0%	5	0.0%
Total Chromium	[µg/L]	1008	<0.001	17.2	10.0	282	50	0.3%	50	0.3%
Lead	[µg/L]	1008	<0.005	4.15	5.00	45.0	50	0.0%	50	0.0%
Selenium	[µg/L]	1008	<0.005	1.73	1.00	14.2	10	0.1%	10	0.1%
Mercury	[µg/L]	1009	<0.0001	0.37	0.50	1.50	1	0.2%	1	0.2%
Asbestos	[mg/L]	554	0.00005	4.55	1.00	<30	n.p.	-	30	0.0%
COD	[mg/L]	1009	1	16.6	15.0	43.0	30	0.4%	30	0.4%

** The samples related to the leaching tests performed with CO_2 saturated water (not in according with UNI EN 12457-2) were not considered.*
n.p.: not provided

the available data, we are not able to clear identify the RA compliance or not, because the D.L. is not enough lower than the respective threshold.

The only parameter that certainly exceeds the less restrictive limits for RAs application in bituminous mixtures, sub-bases for roads and concrete production, etc.) (Table 2, column 2, M.D. 127/2024) are heavy hydrocarbons (C>12), with a percentage of exceedance of 11%. Indenopyrene and asbestos show possible non-compliance (Table 2B).

A comparison between the composition of CDW and RAs is reported in Figure 3, for the most critical parameters. It is important to note that the certificates of analysis related to the produced RAs do not correspond to those of the treated CDW to obtain such RAs; furthermore, for the same parameters, the instrumental detection limits are different. In fact, CDW are analyzed with the aim to verify the non-hazardous classification, while RAs must comply the requirements for their recovery.

It can be observed that the content of PCBs and heavy hydrocarbons (C>12) decreases from treated CDWs to produced RAs. Therefore, the treatments adopted in the CDW recycling plants are able to slightly reduce the content of pollutants. Instead, PAHs, such as benzo(a)pyrene and benzo(g,h,i)perylene, show opposite behaviour: this is caused by the presence of many analytical certificates in which the instrumental detection limit for RA is higher than CDW ones.

Figure 4 shows the effect of CDW type (based on EWC) used to produce the RAs on the content of most critical pollutants in RAs. Regarding heavy hydrocarbons (C>12) and PHAs, such as benzo(a)pyrene and benzo(g,h,i)perylene, the concentrations measured in RAs produced from bituminous mixtures (EWC 17 03 02) are significantly higher and much more scattered than RAs produced from other kind of waste. It is important to note that it is impossible to know the origin of the waste for a considerable number of RAs (reported in Figure 3 as "EWC n.a."). Based on the data analyzed (Figure 2 and Table 1), most of them are probably obtained from the mixed CDW (EWC 17 09 04), therefore with heterogenous quality.

As concerns heavy hydrocarbons, almost all the RAs obtained from bituminous mixtures don't comply the less restrictive limit - 750 mg/kg_{DM} - set by the EoW regulation (Ministerial Decree 127/2024). It should be noted that for this kind of RA are already available EoW criteria provided by Ministerial Decree 69/2018, which does not require the measurement of heavy hydrocarbons in the final product (bituminous conglomerate granulate), but rather requires monitoring the sum of PAHs (with a threshold limit of 100 mg/kg_{DM}) and asbestos (1000 mg/kg_{DM}).

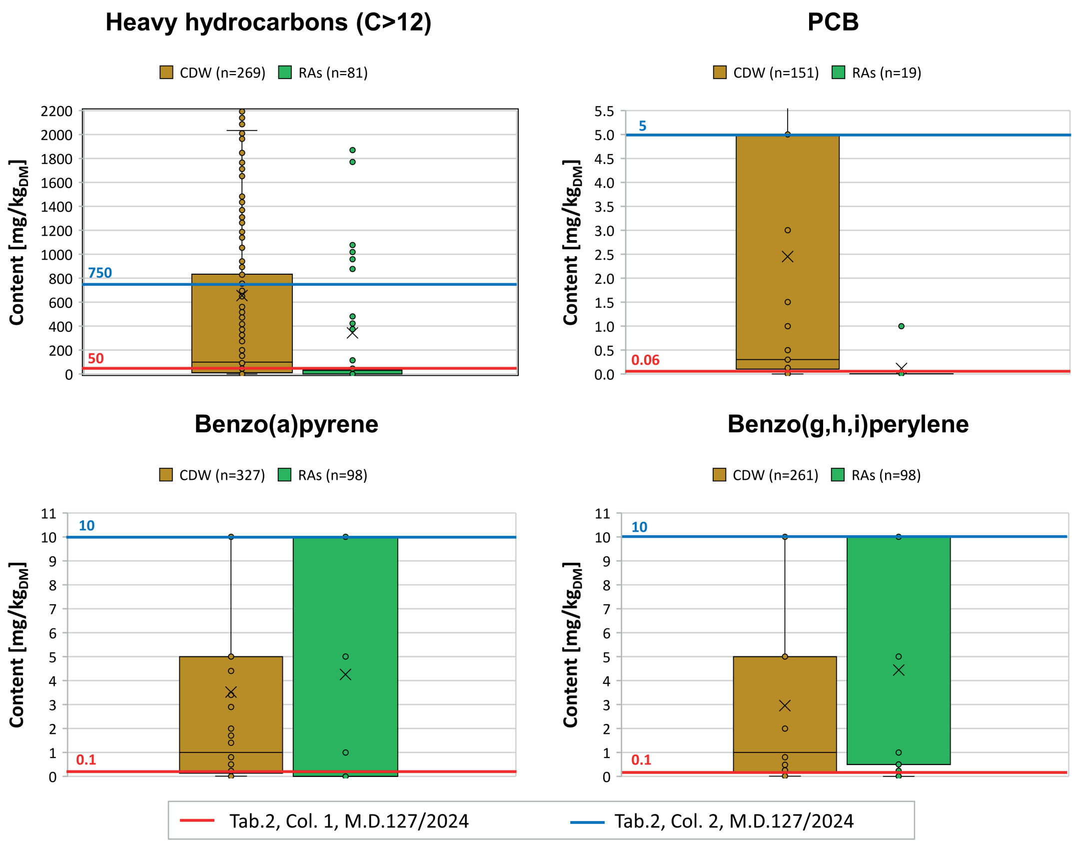

FIGURE 3: Comparison between CDW and RAs chemical composition – most critical pollutants (n: number of analyses).

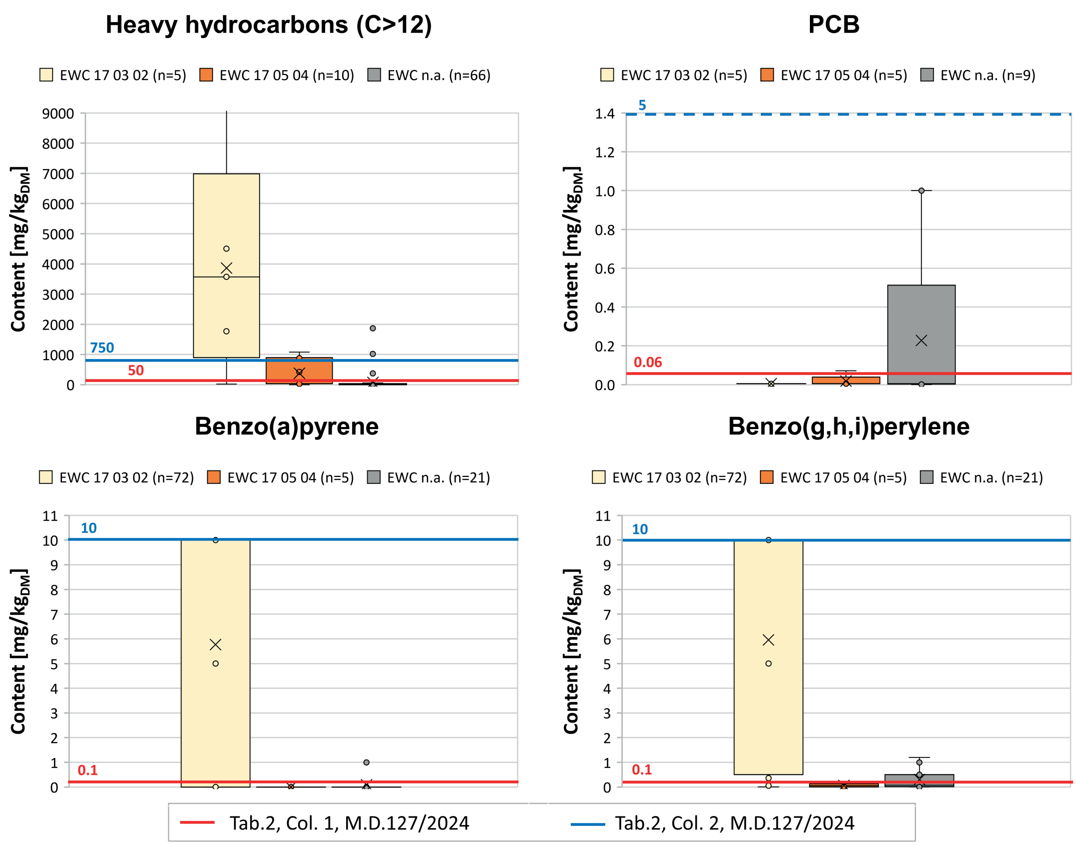

FIGURE 4: Effect of CDW type on the chemical composition of RAs – most critical pollutants (n: number of analyses; EWC n.a.: no information about CDW treated to produce RA).

The RAs obtained from the treatment of soil and rocks (EWC 17 05 04) often show high contents of heavy hydrocarbon that exceed the more restrictive limit (50 mg/kg$_{DM}$) and, occasionally, even the less restrictive limit. This could be due to the fact that during the excavation phase of this CDW, some fractions of bituminous mixtures are also collected and subsequently processed to produce the recycled aggregates.

As concerns PCBs, high content is observed for the RAs obtained by unknown CDW (probably most of them with significant concrete fraction).

3.2 Release of pollutants from recycled aggregates

As reported for the chemical composition, the results of the leaching test on RAs (according to UNI EN 12457-2) were elaborated (Table 3) in order to show the non-compliance both with the Italian EoW criteria (M.D. 127/2024) and the national regulation for waste recovery in simplified procedure (M.D. 186/2006). It can be noted that the limit values are the same, with the exception of sulphate and chloride, and the asbestos (this pollutant is not provided in EoW regulation). For each parameter in the database, minimum, maximum, average and median concentrations are also reported. Also in this case, the average and the median values are calculated considered the values lower than detection limit (D.L.) equal to D.L.. The non-compliance values are highlighted in grey cell.

Unlike the chemical composition, it was not necessary to calculate the possible non-compliance, because, for each parameter, the analysis performed is able to reach concentrations lower than the limit threshold.

It can be noted that there are no particular critical issues. Over 99% of the samples meet the EoW regulation's requirements. Few non-compliances (that do not exceed 1%) are referred to pH, nitrates, COD, fluorides, total chromium, sulphates, barium, nickel, copper, mercury, zinc, and selenium.

Figure 5 shows the results of leaching tests, only for the most critical parameters, using box-plot methodology, in order to see the variability of the pollutants release. It can be observed that:

- concerning pH, despite in most cases it complies with the regulatory limit (in the range 5.5 - 12), the measured values are generally between 9.5 and 11; the higher values are probably due to the presence of cementitious fraction; it is pointed out that pH is one of the most important parameters that affect the release especially of the heavy metals;
- COD is generally between 14 and 22 mg/L; also in this case, although the non-compliance is occasionally, sometimes the measured concentrations are quite close to the limit threshold (30 mg/L); this aspect could be due to the presence of soil fractions;
- total chromium and nickel show scattered concentra-

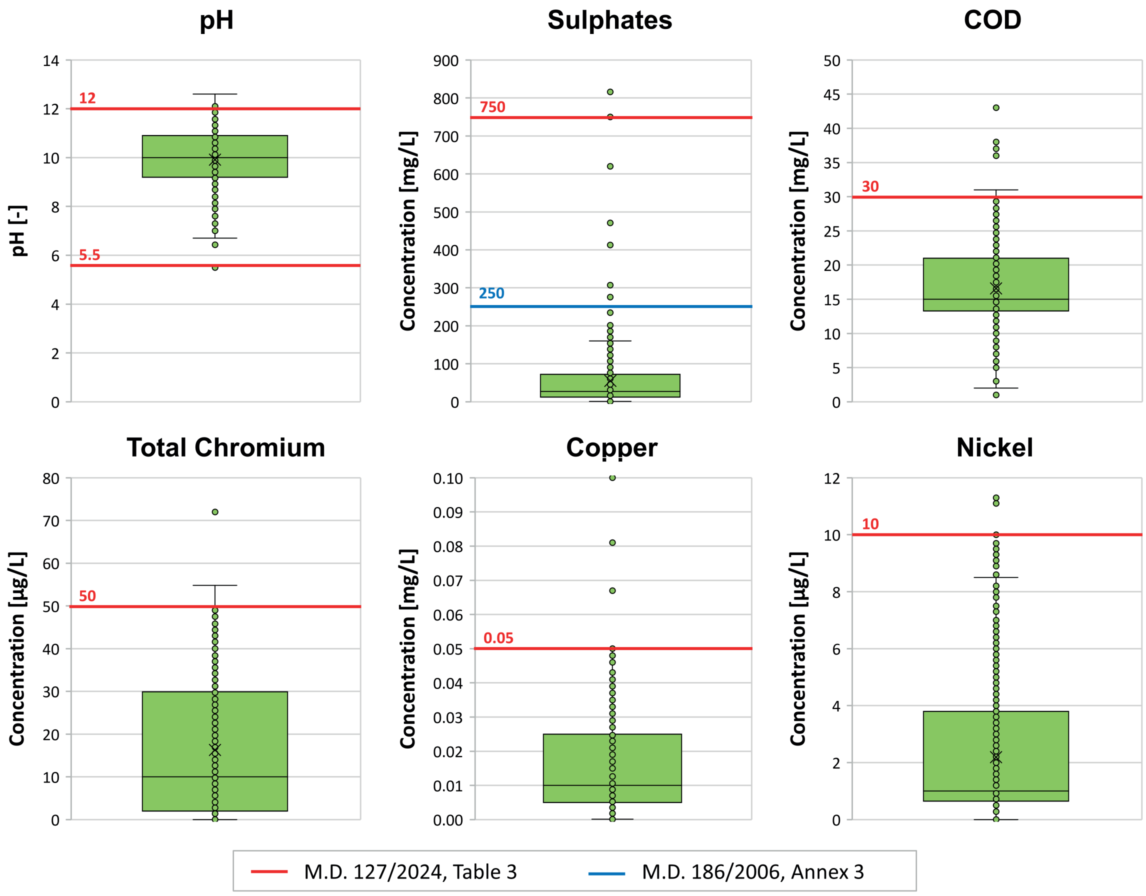

FIGURE 5: Results of leaching tests on RAs – most critical pollutants.

tions; however, the non-compliance with the limits set by EoW criteria (50 μg/L for total chromium and 10 μg/L for nickel) are very low;

- regarding copper, even if only three values exceed the limit values (0.05 mg/L), there are several concentrations close to this threshold;
- as concerns sulphates, most values are below both limit values (250 imposed by the waste recovery regulation and 750 mg/L provided by the EoW criteria), although some values exceed 250 mg/L (threshold for waste recovery in simplified procedure).

As mentioned above, the higher releases of COD (Figure 6) – in few cases also over than EoW limit values - are observed for RAs obtained from the treatment of soils and rocks (EWC 17 05 04) and from unknown waste (probably most of them are RAs derived from mixed CDW). This aspect could be due to the presence of residual soils (derived from the demolition operation) in the mixed CDW sent to the recycling plants.

As might be expected, high releases of total chromium are noted in RAs obtained from cement CDW (EWC 17 01 01). Moreover, RAs derived from unknown waste (n.a. in Figure 6) showed very scattered concentrations ang the highest values, also above the threshold; their quality is higly variable and occasionally cementitious and concrete fractions may be found.

3.3 Environmental and economic implications of non-compliant recycled aggregates

The use of RAs from CDW that do not comply with EoW regulation can have serious environmental and economic consequences. From an environmental standpoint, one major concern is the potential release of contaminants. Heavy metals such as chromium, lead, copper, and zinc can leach into soil and groundwater, posing risks to ecosystems and human health (Diotti et al., 2020; Vu Quoc Hung et al., 2022). Cement residues present in RAs tend to produce highly alkaline leachates, which can disrupt soil chemistry and harm microbial communities (Diotti et al., 2020). Elevated sulphate concentrations are another issue, as they may accelerate chemical degradation processes and contribute to groundwater contamination (Diotti et al., 2020). Furthermore, RAs that include asphalt can release PAHs, compounds known for their toxicity and persistence in the environment (Jandová et al., 2025). Studies also highlight that contaminant loads vary widely among recycled materials, and standard leaching tests may underestimate their ecotoxic potential, making risk assessment more complex (Maia et al., 2018; Vu Quoc Hung et al., 2022).

On the economic point of view, non-compliant RAs create several challenges. To meet environmental safety standards, additional treatments, such as advanced washing, are often required, which significantly increase production costs (Peiris et al., 2025a). If these materials cannot achieve End-of-Waste status, they remain classified as waste, leading to higher disposal costs and reducing their market value (García et al., 2024). This situation undermines the competitiveness of recycled aggregates compared to virgin materials and can discourage investment in recycling technologies (Dias et al., 2022). Moreover, non-compliance may result in exclusion from public procurement processes and green-certified projects, limiting market opportunities (García et al., 2024). Producers also face increased administrative burdens, including more frequent testing and certification, which further raises operational costs (García et al., 2024; Diotti et al., 2020). Ultimately, these factors can lead to greater volumes of waste being sent to landfills, counteracting circular economy goals and diminishing the environmental benefits of recycling (Peiris et al., 2025a).

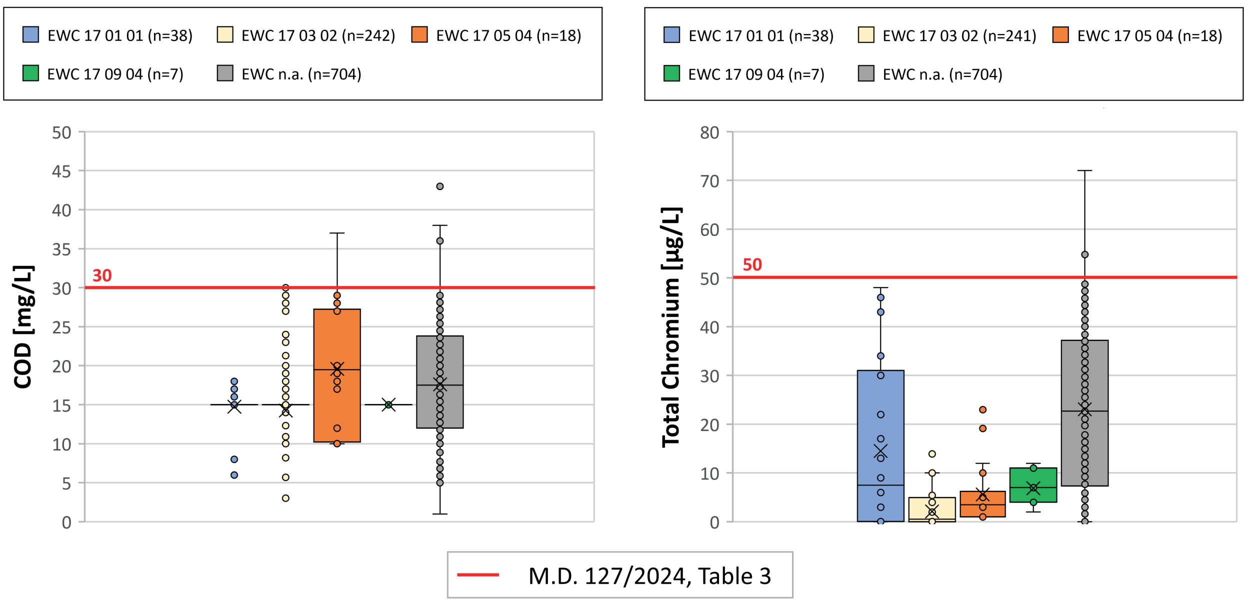

FIGURE 6: Effect of CDW type on COD and total Chromium release from RAs (n: number of analyses; EWC n.a.: no information about CDW treated to produce RA).

4. CONCLUSIONS

To promote waste reuse in the building sector, the Italian EoW requirements for inert waste were published in September 2024. There has been some news, mostly about the addition of different limit values for the pollutants' content depending on the kind of RA application.

This study aims to assess the impact of the EoW regulation's implementation on the viability of recovery by illustrating the quality of RAs in relation to the requirements established by the recent regulation. Therefore, a survey was carried out on 28 Italian recycling plants. The data collected (in 2020 - 2022 period) are referred both to the quality of waste treated by recycling plants (CDW) and to recycled aggregates produced (RAs) ones. About 2500 laboratory certifications (both for chemical analysis and leaching tests) are acquired.

Regarding the content of pollutants in RAs, the most critical parameters are heavy hydrocarbons (C>12), PAHs such as benzo(a)pyrene and benzo(g,h,i)perylene, and PCB. It is important to underline that the use of the collected data does not always allow to assess with certainty the non-compliances with the strictest limits established for the application of RAs in environmental reclamation and filling. In fact, the analysis results' detection limits are often greater than the more stringent threshold values.

The highest concentrations of heavy hydrocarbons and PAHs were detected in RAs from the treatment of bituminous mixtures (EWC 17 03 02). Moreover, for these wastes, there is already an EoW regulation (M.D. 69/2018) that has no requirement for heavy hydrocarbons in the final product (bituminous conglomerate granulate).

Even RAs obtained from soils and rocks (EWC 17 05 04) often show content of heavy hydrocarbons above the most restrictive limit (50 mg/kg_{DM}) and sometimes even above the least restrictive limit (750 mg/kg_{DM}), probably due to the presence of residues of bituminous mixtures during the soil excavation phase.

As concerns the release of pollutants from RAs, any critical issues are shown. For many parameters (pH, nitrates, COD, fluorides, total chromium, sulphates, barium, nickel, copper, mercury, zinc, and selenium) very few non-compliance (always below 1% of total samples) with EoW requirements.

RAs obtained from soils and rocks (EWC 17 05 04) show higher COD release, and RAs from cement waste (EWC 17 01 01) show higher release of total chromium, due to the presence of cementitious and concrete fractions.

Non-compliant recycled aggregates from CDW may leach heavy metals, sulphates, and PAHs, contaminating soil and groundwater. Economically, extra treatments and certifications increase costs, and failure to meet End-of-Waste standards results in landfill disposal and market exclusion. Overall, non-compliance weakens circular economy objectives and limits competitiveness in sustainable construction.

ACKNOWLEDGEMENTS

The Authors wish to thank National Association of Building Constructors (ANCE) for the support during the research work development and data collection, as well as the recycling plants that took part in the survey and supplied the data and analysis (A.e.C. Costruzioni S.r.l.; Beton Eisack S.r.l.; Bonfiglio Alberto S.r.l.; Brusco Raffaello; Cosar S.r.l.; Del Debbio S.p.A.; Ecosistem S.r.l.; Erdbau S.r.l.; Fasanini S.r.l.; Frantoio Fondo Valle S.r.l.; Frassino S.ca.r.l.; F.lli De Pra S.p.A.; Gruppo Gatti S.p.A.; Impresa Milesi Geom. Sergio S.r.l.; Impresa Rota Nodari S.p.A.; Inerti San Valentino S.r.l.; Ircop S.p.A.; Ise S.r.l.; Manelli Impresa S.p.A.; Pizio S.p.A.; PMB S.p.A.; Roncelli Costruzioni S.r.l.; Stroppiana S.p.A.; Vangi inerti S.r.l.). A special thanks to Paolo Olivari, Paolo Cannata and Lorena Favalli for the support given to the study during the data collection.

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