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Review

Reuse or Disposal of Waste Foundry Sand: An Insight into Environmental Aspects

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Abstract: From a circular economy perspective, the recovery and reuse of waste plays a fundamental role. Foundries purchase hundreds of millions of siliceous sands every year to create molds and cores that give shape to the casting. These sands, after several uses, become waste that must be properly recovered or disposed of; they are called waste foundry sands (WFS). The reuse of WFS leads to a reduction in: (i) the consumption of raw materials; (ii) the emissions into the atmosphere; and (iii) the amount of waste sent to landfill—on the other hand, the impact that their use generates on the environment and human health must be carefully assessed. Leaching tests are a fundamental tool for establishing the hazardousness of a waste and its release of contaminants into the environment. This paper presents an analysis of the scientific literature regarding the chemical characteristics of WFS and their release following leaching tests carried out in the laboratory; the environmental standards adopted by the countries that have issued guidelines regarding the reuse of WFS will also be presented.

Keywords: waste foundry sand; environmental behavior; leaching characteristics

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1. Introduction

To limit the consumption of raw materials and the disposal in landfills, it is appropriate to encourage the recovery of material from waste, always considering the consequences that their reuse has on the environment and human health.

Foundries purchase large quantities of virgin sand for the creation of molds and cores necessary for the melting of ferrous and non-ferrous metals; these molds and cores are not reusable, but the sand that composes them, following physical and chemical processes, is reused and reintroduced into the molding cycle. Only when the sand no longer satisfies the physical and chemical requirements for forming is it removed from the molding process, to become waste.

The mold and core forming processes are different, and are generally divided into two main categories: (i) green sand molding, which involves the use of sand mixed with a suitable binder (usually bentonite clay), carbonaceous additives and water; (ii) chemically bonded sand molding, that consists in the use of sands and chemical compounds such as phenolic-urethane, furan and phenolic-formaldehyde resins [1].

Approximately 100 million tons of waste foundry sands (WFS) are generated annually worldwide by the foundry industry [2]; 6 million tons are produced by around 3000 European foundries [3]. WFS represents about 80% of the waste produced by the foundry industries, and its disposal involves high costs; in most cases, foundries rely on companies that, based on chemical and environmental analyses carried out in accredited laboratories, establish the waste nature (hazardous or not) and its possible reuse or disposal in landfill for inert or non-hazardous waste (according to national regulations). Physical (sieving, iron removal) and chemical (calcination) treatments are carried out at the recovery plants, which improve the characteristics of WFS, and make it suitable for the requests of end users; the calcination of WFS, at the range from 450 to 550 °C, is sufficient to remove the phenol originated from the resins [4].

The main options for WFS reuse are the replacement of fine aggregate in concrete [2,5–7], cement factories [8,9], brick furnaces [10–12], embankments [13,14] or structural fills [14,15]; some studies guarantee their suitability for the ceramic [16–19] and glass sectors [20,21] but to date there are no full-scale applications. The unbound applications of WFS that do not involve their immobilization in a matrix are widely used worldwide; this type of use requires greater attention, as WFS, in contact with rainwater, can release contaminants that can affect the conditions of surface and groundwater, increasing risks for human health and the environment.

To measure the release of contaminants into the environment from a solid matrix, leaching tests are carried out. These tests involve a contact (for a certain time and under certain conditions) of the studied material with a liquid to determine which constituents will be leached into the liquid and potentially released to the environment. Understanding the leachate characteristics of WFS is essential in its disposal, environmental impact and potential development for beneficial utilization towards solid waste management.

According to the EU waste Directives [22] WFS can be classified as non-hazardous and hazardous waste, depending on their chemical characteristics. This legal framework addresses the national legislation in EU countries defining the specific criteria for landfill disposal [23] or reuse. The flow chart reported in Figure 1 shows the overall strategy adopted in Italy to assess the determination of reuse/disposal of WFS, including the specific tests required for each final destination.

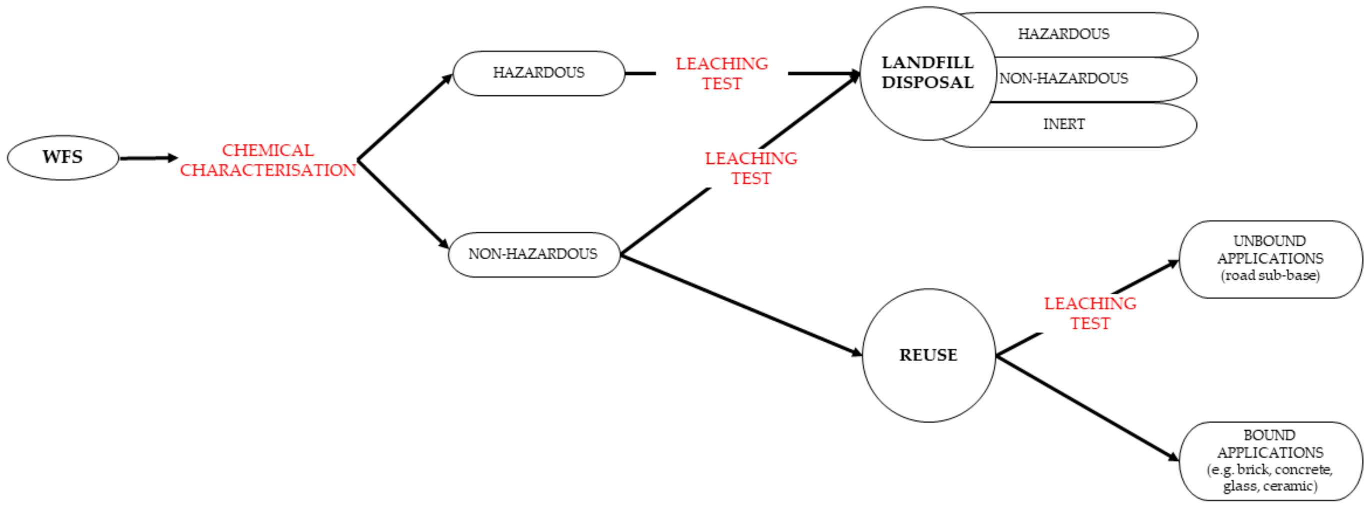

Figure 1. Schematic diagram of WFS.

The reuse option is not only determined on the base of the characterization tests, but market demand can represent an important barrier. To increase the reuse potential of WFS, it is necessary to promote environmental policies, legislation and demonstration activities for new models of circular economy which have been already applied to other industrial sectors to maximize environmental benefits [24–26]. However, a comprehensive evaluation of the circular economy approach is necessary in order to include not only the positive issues, but also the limiting factors such as energy consumption and by-products generated during the reuse process itself [27–29].The aim of this review is to highlight the environmental aspects deriving from the reuse and disposal of WFS, although these often take a back seat and the research topics focus mainly on the physical-mechanical characteristics of the finished products.

2. Methodological Approach

A bibliographic search was carried out on the Scopus portal, with the aim of finding scientific publications (research papers and reviews) on this topic. The keyword “waste foundry sand” was used to make a first screening; the additional keywords “leaching properties” and “environmental behavior” were applied in order to focus on the environmental aspects of WFS reuse or disposal. After a preliminary screening aimed to remove marginally or not related publications, each remaining paper was examined in depth to find eligible works for the review. In addition to this, works published by regulatory bodies on this topic (directive, protocols, etc.) were examined.

3. Foundry Sands Characteristics and Composition

A large amount of sand is used by the metal casting industries to create molds and cores. Sands used in foundries are high-quality silica sands that are recycled and reused several times until they no longer meet required physical characteristics (grain size, grain shape etc.). Classification of foundry sands depends upon the type of binder systems used in metal casting; two types of binder systems are generally used, clay-bonded sand (green sand) and chemically bonded sand. After the casting process is completed, resin-bound sands can be thermally reclaimed to make new molds and cores, while green sands require the addition of new bentonite clay and carbonaceous materials. Table 1 shows the chemical composition of virgin foundry sands (VFS) usually adopted in the foundries. To limit the amount of WFS landfilled, numerous studies have been conducted in recent years to evaluate its reuse as a secondary raw material in various sectors: cement factories [8,9]; concrete [2,5–7]; ceramic [16–19]; and glass industries [20,21]. To evaluate the correspondence with the characteristics required in the various areas, the WFS are subjected to chemical analyses and leaching tests to verify the release of substances that could create risks for human health and the environment.

Table 1. Chemical composition (expressed in %) of virgin foundry sands (VFS) and waste foundry sands (WFS).

Oxide	Virgin Foundry Sands (VFS)			Waste Foundry Sands (WFS)					
	[31]	[32]	[33]	[34]	[30]		[35]	[36]	[20]
				n.r.	GFS	QFS	GFS	n.r.	n.r.
SiO_2	87.9	94.4	91.1	96.7	84.9	95.1	81.9	83.8	92.8
Al_2O_3	4.7	3.4	2.2	0.59	5.2	1.5	10.4	0.81	2.6
Fe_2O_3	0.94	0.58	1.9	0.21	3.3	0.49	1.8	5.4	0.74
Na_2O	0.19	0.1	0.30	0.04	0.50	0.26	0.76	0.87	0.45
CaO	0.14	0.09	0.10	0.03	0.58	0.19	1.2	1.4	0.56
MgO	0.30	0.05	0.30	0.02	0.67	0.19	2	0.86	0.30
SO_3	0.09	n.a.	0.20	0.01	0.29	0.03	0.84	n.a.	n.a.
K_2O	n.a.	0.45	n.d.	0.06	0.97	0.68	0.49	1.1	0.17
TiO_2	n.a.	0.03	n.d.	n.a.	0.19	0.04	n.a.	0.21	0.20
MnO	n.a.	0.01	n.a.	n.a.	0.08	n.a.	n.a.	n.a.	n.a.
P_2O_5	n.a.	0.01	n.a.	n.a.	0.05	0.02	n.a.	n.a.	n.a.
Cr_2O_3	n.a.	n.a.	n.a.	n.a.	0.37	0.21	0.03	n.a.	n.a.
LOI	2.1–12.1	0.79	3.9	n.a.	2.9	1.32	6.9	n.a.	2.1

LOI: loss of ignition; n.a.: not available; n.d.: not detected; n.r.: not reported.

Figure 2 shows the virgin sand for the molds and cores forming process and the WFS after it has been used many times in a foundry.

(a) (b)

Figure 2. Samples of Virgin sand (**a**); and WFS (**b**).

The type of metal casted is the main factor influencing the presence of different element in chemical composition of WFS; chemical composition is influenced also by the type of binder and combustible used. WFS consists primarily of silica sand, coated with a thin film of burnt carbon, residual binder (bentonite, sea coal, resins/chemicals) and dust. As shown in Table 1, the main oxides of waste foundry sand are SiO_2 (more than 80%), Al_2O_3 and Fe_2O_3. According to Exteberria et al. [30], chemical bonded sands (QFS) show higher concentrations of SiO_2 but lower concentrations of Al_2O_3 and Fe_2O_3 than green foundry sands (GFS) oxide composition.

The concentration of metals in WFS reported in Table 2 show that among the heavy metals, those most commonly found in WFS are chromium, nickel and zinc.

Table 2. Range of concentrations of heavy metals in WFS (mg/kg of dry-weight).

Parameter	[37] Number of Samples: 43	[38] Number of Samples: 39	[39] Number of Samples: 110	[40] Number of Samples: 5	[41] Mean of 594 Samples
As	0.04–4.8	0.13–7.8	n.a.	n.a.	0.86
Ba	<8.7–151	n.a	7.4–115	n.a.	14.95
Be	<1.2–3.1	<0.1–0.6	<0.07–0.64	n.a.	0.08
Cd	<5.9	<0.04–0.36	<0.20–0.97	0.55–0.97	0.22
Co	<0.84–95	<0.5–6.6	<0.70–77	n.a.	n.a.
Cr	<1–149	<0.5–115	297–931	47.1–311	114.03
Cu	<23–3318	<0.5–137	<0.5–303	6.1–56	103.60
Hg	n.a.	n.a.	n.a.	n.a.	0.04
Mo	<4.4–9.6	<1–23	0.99–21	n.a.	38.84
Ni	<1.2–2328	1.1–117	41–260	12–82	107.94
Pb	<7.7–25.7	<1–23	<4.2–647	2.4–38	15.72
Sb	<4.5	n.a.	n.a.	n.a.	4.34
Se	n.a.	<0.4–0.44	n.a.	n.a.	0.64
Tl	n.a.	<0.04–0.1	<12	n.a.	0.43
V	<7.4–9.1	<1–11.3	3.49–26	n.a.	n.a.
Zn	<33.4–1640	<10–245	6.06–171	11–82	102.48

n.a.: not available.

There is currently a lack of understanding as to how the foundry process contributes to different levels of organic contaminant and other WFS characteristics. A study by [42] lists the possible harmful organic compounds in WFS related to the type of castings and sands: the possibly existed compounds are significantly different; there is also considerable variability in the contaminant profiles of WFS between foundries, and often within a foundry due to temporal variations [43]. PAH (polycyclic aromatic hydrocarbon) was found in waste foundry sands [41,42,44], with higher concentrations in green sands [42]. Concerning the chemical binded waste sands, the sum of analyzed PAH compounds in furan/acid sands

(0.2–0.7 mg/kg) and silicate sands (0.36 mg/kg) were lower than those in phenolic/ester sands (1.2–2 mg/kg) and in green sands (9.4–29 mg/kg) [42]. Zhang et al. [44] showed high concentrations of organic compound in WFS (sum of analyzed organic compounds 55–3176 mg/kg), composed mostly of phenols (28–676 mg/kg) and naphthalene (2-methyl-: 1–994 mg/kg; 2,6-dimethyl-: 0.5–630 mg/kg).

4. WFS Leaching Characteristics

The determination of the release of pollutants from waste samples represents one of the ways to evaluate the hazardousness of a waste and its possible reuse. Since there is no relationship between the total content of contaminants in a solid waste and their leachability, leaching tests are also used to determine the release of pollutants from solid waste and their possible impact on groundwater.

Leaching batch tests are conducted according to methods established by the regulatory bodies. Among these, the most commonly used with WFS are:

- TCLP (Toxicity Characteristic Leaching Procedure) EPA method 1311: the TCLP test is the USEPA leaching procedure for determining the characteristics of hazardous waste. This test is designed to determine the mobility of both organic and inorganic compounds present in liquid, solid and multiphasic wastes; it involves a simulation of leaching through a landfill.
- SPLP (Synthetic Precipitation Leaching Procedure) EPA method 1312: the intent of this leachate procedure is to simulate the conditions of an acid precipitation where rain passes through the waste. It is designed to determine the mobility of both organic and inorganic compounds present in liquids, soils and wastes; it can be used to evaluate the impact of contaminated soils on groundwater. The extraction fluid consists of slightly acidified deionized water, which is formulated to simulate natural precipitation.
- EN 12457-2: This part of four European Standards specifies a compliance test providing information on leaching of granular wastes and sludge under the experimental conditions specified hereafter, and particularly a liquid to solid ratio of 10 L/kg dry matter. It applies to waste which has a particle size below 4 mm without or with size reduction. This test is adopted in Italy for the evaluation of waste disposal or its reuse.
- EN 12457-4: This part of the European Standard specifies a compliance test providing information on leaching of granular wastes and sludge under the experimental conditions specified hereafter, and particularly a liquid to solid ratio of 10 L/kg dry matter. It applies to waste which has a particle size below 10 mm without or with size reduction.

Table 3 shows the main operational criteria of most adopted leaching test methods.

Table 3. Operational criteria of the leaching tests according to TCLP, SPLP, EN 12457-2 and EN 12457-4.

Operation Criteria	TCLP	SPLP	EN 12457-2	EN 12457-4
Type of leachant	Acetic acid solution	Sulphuric/nitric acid solution	Demineralized water	Demineralized water
Particle size reduction	<9.5 mm	<9.5 mm	<4 mm	<10 mm
Liquid-to-solid ratio	20:1 (by mass)	20:1 (by mass)	10:1 (L/kg)	10:1 (L/kg)
Extraction period (stirring speed)	18 ± 2 h (at 30 rpm)	18 ± 2 h (at 30 rpm)	24 ± 0.5 h (at 10 rpm)	24 ± 0.5 h (at 10 rpm)
Leachant renewal step	No	No	No	No

TCLP is the most widely used leaching test method [41,45–47]. The metal concentrations in the eluates of WFS usually respect the limits imposed by the TCLP; the concentrations of some metals, such as Ag and Sb, are even always below the quantification limit of the instruments used. WFS from copper-based facilities contain relatively higher levels of Cu, Pb and Zn than from other facilities; WFS from iron/steel-based facilities contain relatively higher levels of Fe and Mn than from other facilities [41]. Alves [46] reported that some of the heavy metal concentrations (i.e., Ba, Hg, Mn, Ni and Pb) were found to exceed drinking water and groundwater maximum contaminants level (MCLs). When samples were tested with TCLP (more aggressive leaching protocol) and SPLP (slight acidification), the first one resulted in the most aggressive protocol, with an increase in the release of metals due to the low pH-related conditions [48]. High concentrations of Acetone and Naphthalene were reported both in bleed water released from fresh materials (Acetone max 1540 µg/kg, Naphthalene max 619 µg/kg) and TCLP method leachates (Acetone max 115 µg/kg, Naphthalene max 616 µg/kg) [49]. Similar results were reported in [41].

In Table 4, the concentrations of pollutants in leachate obtained with TCLP standards from different authors [13,34,37–40,43] are listed; the mean concentrations are always below the limit provided by TCLP criteria, except for Pb [36] and Hg [50].

Table 4. Results of leaching test carried out on WFS according to TCLP (mg/L).

Parameter	[45]	[47]	[46]	[44]	[41] *	[13] *	[50] *	US EPA TCLP Criteria
Ag	<0.007	<0.04	<0.005	n.d.	0.004	n.a.	n.a.	5
Al	n.a.	n.a.	<0.03–10	0.192–1.95	1.785	n.a.	n.a.	n.p.
As	n.a.	<0.001–2.4	<0.01	0.001–0.36	0.031	n.a.	n.a.	5
B	n.a.	n.a.	0.01–2.7	0.015–0.06	n.a.	n.a.	n.a.	n.p.
Ba	<0.004–0.748	<0.86–1.13	0.22–3.9	0.018–1.28	0.639	0.133	n.a.	100
Be	n.a.	<0.01–0.043	<0.01	0.001–0.005	n.a.	n.a.	n.a.	n.p.
Cd	<0.003	<0.01–0.065	<0.004	0.0005–0.005	0.004	n.a.	0.003	1
Co	n.a.	n.a.	0.003–0.04	0.001–0.007	n.a	n.a.	n.a.	n.p.
Cr	<0.007–0.085	<0.46	<0.01–0.23	0.01–0.011	0.042	<0.1	0.100	5
Cu	<0.005–0.370	<0.1–44	<0.01–0.11	0.008–0.039	0.521	<0.1	0.172	n.p.
Fe	n.a.	n.a.	0.61–384	0.04–4.4	61.78	n.a.	n.a.	n.p.
Hg	n.a.	n.a.	<0.006	n.a.	<0.001	<0.001	**0.310**	0.2
Mg	n.a.	n.a.	0.33–56	0.71–5.1	n.a	n.a.	n.a.	n.p.
Mn	n.a.	n.a.	0.07–6.1	0.04–0.64	1.009	n.a.	3.830	n.p.
Mo	n.a.	n.a.	<0.015	0.005–0.009	n.a	n.a.	n.a.	n.p.
Ni	<0.020	<0.14–1.71	<0.005–0.12	0.002–0.03	0.183	<0.1	n.a.	n.p.
Pb	<0.042–**11.04**	<0.05–1.13	<0.009–0.17	0.007–0.03	0.222	<0.1	0.039	5
Sb	n.a.	<0.02	<0.005	0.007–0.03	n.a	n.a.	n.a.	n.p.
Se	n.a.	n.a.	<0.009	0.087	0.041	<0.05	n.a.	1
V	n.a.	n.a.	<0.015–0.03	0.024–0.09	n.a	<0.1	n.a.	n.p.
Zn	<0.006–3.79	<0.41–43	0.14–5.4	0.22–0.98	1.006	1.067	0.360	n.p.

* Mean values; **Bold values** exceed the US EPA TCLP criteria; n.a.: not available; n.p.: not provided.

In European studies, the samples are subjected to leaching tests, according to the EN 12457-2 and EN 12457-4. According to a Polish study [40] conducted on WFS disposed in a landfill during the last 40 years, the content of Cu, Zn, Ni, Cd, Pb and Cr in eluates was determined to be below the limit of quantification. Other leaching tests were conducted with different leachants, and the highest heavy metal release was obtained with the use of HCl (0.1 M) and EDTA (Disodium salt dihydrate, 0.05 M). Another study conducted by Bozym [51] reported that the leachability of metals from WFS was minimal (below the limit value for inert landfill), despite the high total content of these metals in the waste. Instead, Merve Basar [35] showed that Ni, Cr, Zn, F^- (fluoride) and TDS (Total Dissolved Solids) resulted to be above the limits set by EU for disposal in inert waste landfill [23] (concentrations are reported in Table 5); furthermore, DOC (Dissolved Organic Carbon) concentration was found to be above the EU hazardous landfilling acceptance limits. Leaching tests at different pH values were also performed on concrete mixes made with the use of WFS as a substitute for fine aggregate (from 0 to 40%); it is verified that the concentrations of Ni, Zn, Cr, TDS, F^- and DOC in the eluate of the mixtures with different WFS content comply with EULFD (European Landfill Directive) limits for pH levels ranging from 4.0 to 9.0.

Table 5. Leachate contaminants concentration using EN 12457-4 and EULFD limits (value in mg/kg).

	Ni	Zn	Cr	F^-	TDS	DOC
WFS leachate [35]	**1.4**	**5.9**	**1.2**	**18.9**	**47,310**	**<u>894</u>**
Limit value of inert landfill [23]	0.4	4	0.5	10	4000	240
Limit value of non-hazardous landfill [23]	10	50	10	150	60,000	800

TDS: Total Dissolved Solids; DOC: Dissolved Organic Carbon; **Bold values** exceed the limits for inert landfill; **<u>Bold and underlined values</u>** exceed the limits for non-hazardous landfill.

Kaur et al. [36] investigated the leaching behavior of fungal-treated WFS according to ASTM D3987 (shake extraction of solid waste with water), and showed that fungus (*A. niger*) can reduce the release of metals such as Cd, Cr, Fe, Mo, Mn, Ni and Pb.

Ji et al. [42] analyzed chemical and leaching characteristics of WFS; eleven samples were collected from several foundries that use different type of binders. The leaching characteristics were carried out according to the column test method (NEN7343) developed in the Netherlands, which has been withdrawn and replaced by EN 14405. This protocol specifies an up-flow percolation test to determine the leaching behavior of inorganic and non-volatile organic substances from granular waste materials under standardized percolation conditions. The release of metals is very low, except for some elements such as Cr, Cd and Zn usually contained in the casted metal. There seems to be no relation between metal concentrations in leachate and the type of binder used for molds and core.

Yazoghli-Marzouk et al. [52] carried out field leaching tests with the aim of evaluating the release over several years, due to the use of WFS as road sub-base layer, and found that the laboratory tests were conservative, and applied more severe leaching conditions (liquid/solid) than in the field test.

To date, there is limited understanding of nature, dynamics and impact of organic and metallic compounds derived from WFS on the environment. This is related to the poor knowledge of the complete characterization of the WFS.

5. Environmental Standards for WFS Reuse

The reuse of waste is regulated by national law.

In Italy, for instance, Ministerial Decree 5 February 1998 [53], updated with Ministerial Decree n. 186/2006 [54], regulates the reuse of non-hazardous waste in simplified recovery procedures. This regulation reports a series of available reuse for WFS, and provides environmental standards with which WFS must comply for uses such as the construction of embankments and road foundations.

A French work [55] defines guidelines for the reuse of WFS in road construction; three scenarios, which mainly depend on the thickness of the layer, are evaluated, and different threshold for leaching tests are provided. The limits imposed are slightly above the limit values for admission to landfills for inert waste, but well below those for admission to landfills for hazardous waste imposed by EU legislation 2003/33/EC [23].

In the USA, each state has different thresholds of allowable concentrations in the leachate for scenarios in which WFS can be reused [56]. Among all reuses, manufacture of products (e.g., asphalt, bricks, concrete block, cement, etc.) poses the least environmental risk, and consequently has the least-stringently regulated reuse. In several states, WFS needs only to be qualified as non-hazardous (according to TCLP) or marginally non-hazardous (using a percentage of RCRA TC levels, e.g., Iowa). In most states, however, the maximum allowable leachate concentration for constituents of concern ranges from values equivalent to federal drinking water standards (i.e., Illinois state) to 30 times these values. Reuse as structural fill, or as backfill and pipe bedding, requires more stringent thresholds. Based on the different local standards, USEPA developed a toolkit to assist states in WFS reuse; this is a six-step process that guides from developing a reuse program to post-application monitoring [57].

Table 6 compares, for different countries, the limit values of pollutant released in the leachate for WFS reuse in road base construction.

Table 6. Limit values in the leaching test for the use of WFS by French guidelines, and Illinois and Iowa for structural fill.

Parameter	France [55]			USA [56]	
	Scenario 1 (mg/kg)	**Scenario 2 (mg/kg)**	**Scenario 3 (mg/kg)**	**Illinois (mg/L)**	**Iowa (mg/L)**
Ag	n.p.	n.p.	n.p.	n.p.	4.5
As	0.6	0.6	0.6	0.05	4.5
Ba	25	25	25	2.0	90.0
Cd	0.05	0.05	0.05	0.005	0.90
Cr	0.8	0.6	0.6	0.1	4.5
Cu	3	3	3	5.0	n.p.
Hg	0.01	0.01	0.01	n.p.	0.18
Fe	n.p.	n.p.	n.p.	5.0	n.p.
Mn	n.p.	n.p.	n.p.	0.15	n.p.
Mo	0.6	0.6	0.6	n.p.	n.p.
Ni	4	2	0.5	n.p.	n.p.
Pb	0.6	0.6	0.6	0.0075	4.5
Sb	0.7	0.4	0.08	n.p.	n.p.
Se	0.1	0.1	0.1	0.05	0.90
Zn	20	10	5	n.p.	5.0
Nitrate	n.p.	n.p.	n.p.	10.0	n.p.
Fluoride	60	30	13	4.0	n.p.
Chloride	1000	1000	1000	250.0	n.p.
Sulphate	10,000	5000	1300	400.0	n.p.
Phenol	2	2	1	n.p.	n.p.
Soluble fraction	n.p.	n.p.	5000	n.p.	n.p.
TOC	30,000	30,000	30,000	n.p.	n.p.
BTEX	6	6	6	n.p.	n.p.
Benzene	n.p.	n.p.	n.p.	0.005	0.45
PCB	1	1	1	n.p.	n.p.
Hydrocarbons	500	500	500	n.p.	n.p.
PAH	50	50	50	n.p.	n.p.

Scenario 1: maximum width 3 m; scenario 2: maximum width 6 m; scenario 3: no limit on maximum width; n.p.: not provided. TOC: total organic carbon. BTEX: benzene, toluene, ethylbenzene and xylene. PCB: polychlorinated biphenyls. PAH: polycyclic aromatic hydrocarbons.

Legislative requirements are quite different, and there is a lack of well-defined management strategies for beneficially reusing WFS. Therefore, evaluating the impact on environmental matrices assumes a fundamental role.

5.1. End of Waste Criteria

One of the main barriers hindering the reuse of WFS is their qualification as waste, and regulatory bodies are therefore drafting Decrees (EoW-End of Waste Decrees) to define the criteria for waste to become a secondary raw material.

According to European Waste framework Directive 2008/98/EC [58] and subsequent modifications and integrations adopted with European Directive 2018/851/EC [22], the general EoW criteria are the following:

1. the substance or object is to be used for specific purposes;
2. a market or demand exists for such a substance or object;
3. the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products;
4. the use of the substance or object will not lead to overall adverse environmental or human health impacts

In Italy, a specific EoW regulation for WFS is not available, though the Lombardy Region promoted the proposal of Guidelines for the management of WFS [59] by the Technical Committee observatory for the circular economy and the energy transition.

Queensland region (Australia) adopted an EoW Code for foundry sands setting threshold values for the concentration of contaminants on dry weight waste, without giving limit value on eluate characteristics. Different scenarios are evaluated, considering: (i) bound applications where the resource is encapsulated or chemically transformed and incorporated into a final product; (ii) unbound applications and manufacturing of compost, mulch and soil conditioner; and (iii) unrestricted use and manufacturing of general-purpose soil—unbound uses require more safety environmental features, with lower heavy metals and organic compounds concentrations [60].

5.2. Ecotoxicity Tests

Ecotoxicology studies the adverse effects that a certain substance or a mixture of substances may have on living organisms representative of a specific environmental compartment. For the execution of the ecotoxicological evaluation, different organisms are used.

Few studies described the application of biological tests to different reused wastes [61], and even fewer concern the toxicity of WFS, which is closely related to metal and organic contaminants present in both the solid material and aqueous leachate. For this reason, and because of the destination of the WFS, the selected test organisms are representative of the terrestrial and aquatic compartments.

In a soil-related WFS reuse study [44], the correlation between soil microbial toxicity and contaminated sands is described by a linear model. Leachates from sands are also a source of toxicity for different living organisms. Zhang et al. [62] described different inhibition effects on the luminescent bacteria *Vibrio fischeri*. Curieses and co-workers [63] assessed the toxicity/genotoxicity of foundry sands on the earthworm *Eisenia fetida*. A comprehensive toxicological evaluation of extracts of concrete containing WFS was performed on crustacean *Daphnia magna*, *Allium cepa* (onion roots) and *Eisenia fetida* [64].

5.3. Risk Assessment

A risk-based approach should be pursued when reusing waste in scenarios that can impact the environment and human health. To make an effective risk assessment, the following are important: (i) identification of hazardous substances associated with the material; (ii) definition and quantification of reuse scenarios; and (iii) conceptual models of sources, pathway and receptors. The risk assessment procedure is widely applied to landfills and contaminated sites [65,66]. In recent years, the risk assessment methodology has also been applied to waste reuse in unbound applications. An example of this is chemical risk assessment on BOS (Basic Oxygen steelmaking) and EAF (Electric Arc Furnace) slags [67]. A risk assessment protocol on WFS in soil-related applications has been developed by USEPA [47] in order to evaluate three different scenarios (use as sub-base in roadway constructions, use in soil-less potting media and blending in manufactured soils) and different pathways such as inhalation, groundwater ingestion and soil ingestion. USEPA concluded that the reuse of WFS, when conducted in an environmentally sound manner, can contribute positive environmental (including energy savings, reduced greenhouse gas emissions and water savings) and economic benefits.

6. Conclusions

In most cases, WFS is not hazardous both as regards the limits imposed by the TCLP and by European legislation; despite this, the reuse of WFS is often hindered by its qualification as waste. To promote a circular economy, it is essential to introduce EoW Decrees for WFS, which facilitate their reuse and at the same time protect the environment and human health.

Although in most cases the compounds present in WFS are the same, there is a great variability in the concentrations found due to the type of casting, the type of binders and additives used. Organic compounds such as PAHs and phenols were found, with a wide range of concentrations in WFS.

As concerns the leaching of pollutants, the use of different tests and the variability of WFS make it difficult a comparison among the studies available. However, the metal leaching is low, almost always below the limits imposed by current regulations, except some elements contained in the metal casted (e.g., Pb and Hg). More attention should be paid to the presence of organic compounds in the eluates even if no limits are envisaged by the legislation. Even if the concentrations of the individual pollutants are below the expected limits, their combined effect could create environmental problems, and for this reason, it is recommended to carry out ecotoxicological tests to verify the effect of reusing WFS on the environmental matrix.

In order to have a more complete picture and to create an updated database, it would be advisable to carry out a risk assessment relating to different uses and in different conditions (e.g., precipitation, evaporation, etc.). The definition of a dataset with the various environmental analyses could also be useful in terms of connecting cause and effect between the many variables involved.

In conclusion, it is recommended that more research should be supported, and that this will lead to a deeper knowledge on the theme.

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