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Trace elements in oil shale ashes and waste wood ashes and their leachability with a focus on chromium

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Abstract. *In Estonian oil shale power plants, ash is transported to disposal sites using a wet transport method. Due to regional climatic conditions, where annual precipitation exceeds evaporation, part of the recirculated ash transport water has to be periodically discharged into natural surface waters. This discharge practice raises concerns about the potential environmental impact of the discharged water. This paper investigates the leaching behavior of several trace elements from oil shale ash, demolition wood ash, and their mixtures, with a focus on chromium. In particular, the occurrence, mobility, and oxidation state of chromium in the leachate are considered using the example of the mentioned ashes. The possible effect of ash content, influenced by fuel type and the liquid-to-solid (L/S) ratio, on trace element concentrations in the discharged water was studied. In leaching tests with 100% oil shale ash, the chromium concentration in the circulating water increases only slightly when circulating water from the oil shale ash field is used as the leaching medium. On the one hand, the amount of chromium and other trace elements leached from oil shale ash depends on the L/S ratio. At the same time, it is known from the literature that oil shale ash is also capable of binding chromium. The release and concentration of chromium in the leachate increase significantly as the proportion of waste wood ash rises, compared to tests using 100% oil shale ash. Consequently, the concentration of chromium in surface water, depending on the specific ratio of oil shale to waste wood used in co-combustion, can easily exceed the nationally permitted limit value.*

Keywords: *oil shale ash, chromium leaching, trace elements, co-combustion, water contamination.*

1. Introduction

Oil shale has been used for power generation in Estonia since the 1930s and has dominated local power generation since the 1970s, providing reliable

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power and energy security. Of all the oil shale-fired power plants in the world, the largest ones are located in Estonia. Recently, an oil shale power plant was also commissioned in Jordan [1]. However, the use of oil shale in energy, like other fossil fuels, has been accompanied by environmental problems, such as air, water, and soil pollution, landscape change, and biodiversity loss [2]. Therefore, in recent years, Estonia has tried to reduce its dependence on oil shale and increase the share of renewable energy. The share of oil shale use in energy has decreased significantly over the last decades. Between 1991 and 2008, oil shale accounted for 84–95% of the fuel used in electricity production. By 2020, this share had decreased to 40% [3], but it increased to 57% by 2022 [4]. Oil shale is gradually being replaced by other energy sources, mainly renewables such as biomass, wind, and sun.

There are several reasons for the decline in oil shale use. One is the European Union's climate policy, which aims to reduce greenhouse gas emissions by at least 55% by 2030 and increase the share of renewable energy [5]. Additionally, the Estonian Energy Sector Development Plan until 2030 sets the goal of reducing oil shale use in electricity production and increase the share of renewable energy sources to 50% of electricity consumption [6].

To help achieve fossil fuel-related CO_2 reduction goals, the European Union Emissions Trading System (ETS) was established. Indeed, the rising price of CO_2 in the ETS, which has been mainly fluctuating between 80 to 100 euros per metric ton over the last two years, has made electricity generation from fossil sources less competitive. This price strongly impacts the cost of electricity generated from oil shale, as the associated CO_2 emissions per MWh of electricity generated in circulating fluidized bed (CFB) power plants are about 0.9 to 1.0 tons [7].

One way to reduce CO_2 emissions from fossil fuel-fired power plants is to employ CO_2 capture (CC) technologies. However, this is associated with a significant energy penalty, the extent of which depends on the specific technology used [8]. Moreover, many CC technologies are still in the development phase, hindering widespread practical application. An easier legislative way to reduce CO_2 emissions is the partial or complete replacement of fossil fuels (such as coal or oil shale) with biomass as a renewable fuel. Partial replacement is possible in existing power generation units without significant reconstruction. This option is available, for example, at Balti Power Plant and Auvere Power Plant, both of which can use up to 40% woody biomass for energy production. Although the use of such a fuel mix is only a partial solution, it still provides a significant reduction in fossil CO_2 emissions. Additionally, if CC technology is applied in conjunction with these fuel mixes, it is possible to achieve negative CO_2 emissions.

On the other hand, although using biomass can help reduce CO_2 emissions, there is increasing concern about the excessive use of woody biomass, such as wood chips or pellets, in power production [9]. Therefore, it is preferable to use waste wood, such as demolition debris, instead of "fresh" woody biomass

[10], even though these wastes are often contaminated with various trace elements [11]. Waste wood ash (WWA) can contain contaminants such as As, Pb, Cu, Cr, and Zn, and their concentrations often exceed recommended national limits [12]. For example, Cr and Cu in waste wood primarily originate from chemical treatments applied to impregnated wood, with concentrations reaching several thousand mg/kg [13]. The Cr content in WWA can be as high as 9 g/kg_{DW}, although it depends on the Cr concentration in the waste wood and the proportion of waste wood used in co-combustion with other fuels. In contrast, oil shale ash (OSA) typically has Cr levels below 75 mg/kg_{DW} [14].

Studies have shown that the mobility of Cr in OSA is relatively limited at the material's natural pH. For example, after two sequential standard leaching tests, up to 0.3% of Cr from OSA can be leached into the aqueous environment [15]. The leaching of Cr from OSA depends on the firing technology and ash collection location. Its mobility correlates strongly with Ca and Mo [16].

Studies also show that the release of potentially hazardous elements, including Cr, from OSA is significantly lower than the national and EU permissible limits for landfill leachates [17]. According to the literature, trivalent chromium (Cr(III)) compounds are sparingly soluble in water, whereas hexavalent chromium (Cr(VI)), the most toxic form of Cr, is predominantly found in ash leachates at pH levels above 8, where Cr(III) can be oxidized to Cr(VI) [18, 19].

Consequently, this paper investigates the behavior of various trace elements in OSA and WWA streams, as well as mixtures of these ashes. In particular, the mobility of Cr (mainly Cr(VI)) from OSA and WWA to leachate is considered, focusing on the possible effect of the trace element content and the L/S ratio. Knowledge of the behavior of trace elements in the described system is essential due to their potential environmental impact. These elements are leached not only during the wet transport of the ash to the landfill but also by precipitation, which often exceeds natural evaporation rates in many regions, leading to excess water from ash fields that must be discharged into natural water bodies.

2. Materials and methods

2.1. Ashes used in the study

Two types of ashes and their mixtures in different ratios were used in the experiments:

- **OSA** was obtained from an oil shale power plant in eastern Estonia. It was a mix of bottom ash (ca 30%) and fly ash (ca 70%), reflecting the typical proportions from an oil shale circulating fluidized bed combustion (CFBC) boiler [14], based on the ash content of the fuels.
- **WWA** was produced by incinerating waste wood at 800 °C in a boiler in the TalTech laboratory (Department of Energy Technology, Tallinn

> University of Technology). Approximately 25 kg of waste wood was selected from the coarser fraction produced during the crushing process. This selection included a diverse range of waste wood materials – such as wood, sawdust board, painted wood, etc. – to ensure a representative mix.

These ashes were used in the TalTech laboratory to produce ash blends for the study.

2.2. Characterization of ashes and leachant

The chemical composition of the ashes was measured by means of X-ray fluorescence (XRF). A Primus II XRF spectrometer (Rigaku Corporation, Japan) was used for XRF analysis. The measurements were conducted in an accredited TalTech laboratory following the standard ISO 29581–2:2010(E). The chemical composition of OSA and WWA is presented in Table 1, where the loss on ignition (LOI) refers to the sample weight loss at 950 °C.

Table 1. Chemical composition of waste wood ash and oil shale ash, wt%

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	LOI
Waste wood ash	1.44	4.01	5.07	41.8	1.95	1.99	1.83	30.5	1.52	4.50	1.6
Oil shale ash	0.15	5.65	4.06	21.5	0.15	6.15	1.39	40.5	0.27	2.90	15.2

The concentration of trace elements, including Cr, in ashes and leachant (circulating water (CW) from the oil shale power plant's ash field) was analyzed in the TalTech laboratory using the inductively coupled plasma mass spectrometry (ICP-MS) method, in accordance with the EN ISO 16968:2015 and EVS-EN ISO 17294-2:2016 (-1:2006) standards, respectively. The Cr(VI) content in CW was measured by an accredited laboratory using the APHA SM 3500-Cr B (2017) method. The concentrations of trace elements in WWA, OSA, and the leachant are presented in Table 2.

In all samples, total Cr was analyzed, as required by the Ministry of the Environment for effluents discharged into natural water bodies, which are subject to a regulatory limit of 50 μg/L [20].

The leachant used in the leaching tests was CW from the wet ash removal system, collected near the outlet of the sedimentation pond at the ash field. In some cases, distilled water was used as an alternative leachant. Table 3 includes selected parameters of CW, in addition to the trace element concentrations shown in Table 2. Further details on the parameters of CW can be found in the literature [21].

As indicated in Table 3, the initial concentration of total Cr in CW used for the laboratory leaching tests was 86.5 μg/L, containing over 90% of highly soluble and toxic Cr(VI) on average.

Table 2. Concentrations of selected trace elements in oil shale ash, waste wood ash, and circulating water used in the study

Element	Waste wood ash, mg/kg	Oil shale ash, mg/kg	Circulating water, µg/L
As	13.7	10.0	18.3
Cd	8.22	3.24	0.03
Cr	**269**	**29.7**	**86.5**
Cu	401	9.89	0.33
Ni	65.2	17.6	5.62
Pb	513	28.9	0.48
Zn	6409	79.7	n.d.*

* n.d. – not determined.

Table 3. Selected parameters of the circulating water from the sedimentation pond

pH	EC, mS/cm	Cl^-, mg/l	SO_4^{2-}, mg/l	Cr, µg/L (measured range)	Cr(VI), µg/L (measured range)
12.34	12.57	644	483	86.5 (76–110)	81 (60–100)

2.3. Leaching tests

Laboratory leaching experiments were conducted in accordance with the EVS-EN 12457-4:2002 standard [22], except that the L/S ratio was varied. For the leaching tests, the ash and leachant (either circulating or distilled water) were placed in plastic containers and continuously mixed on a horizontal shaker for 24 hours. After mixing, samples were allowed to settle for at least two hours. For Cr and other trace element analysis, samples were collected from the clarified water and filtered through syringe filters with a pore size of 0.22 µm. The L/S ratio was chosen based on the actual water flow rate used for ash transportation at Baltic Power Plant, as well as the fuel flow rate, considering the ash content of the fuel and potential fuel mixes (up to 40% of energy from biomass/wood chips; calculated based on calorific values of 10.86 MJ/kg for wood chips and 8.50 MJ/kg for oil shale). At an L/S ratio of 16, the boilers operate at full capacity with oil shale, producing about 110 t/h of OSA. When the power unit operates with a fuel mix in which 40% of the energy is obtained from wood chips, the L/S ratio equals 25 if the ash transportation water flow rate is not adjusted. The test plan is detailed in Table 4. In some leaching tests, distilled water (DW) was used to elute the solids for comparison.

Table 4. Leaching test study plan

Oil shale ash / waste wood ash, %	L/S (liquid*/solid) ratio	Leachant
100/0	16, 20, 25, 35, 50	CW
100/0	20, 50	DW
90/10	16, 20, 25, 35, 50	CW
90/10	20, 50	DW
80/20	16, 20, 25, 35, 50	CW
0/100	16, 20, 25, 35, 50	CW

* The volume of leachant used in the experiments was 500 mL.

3. Results and discussion

3.1. Trace elements in ashes with a focus on chromium

With some rare exceptions, Cr is predominantly found in nature as relatively inert and water-insoluble Cr(III), in forms such as $Cr(OH)_3$ or Cr_2O_3 [23, 24]. In contrast, Cr(VI) is generally recognized as an anthropogenic contaminant associated with industrial pollution. Thus, Cr(VI) primarily originates from the transformation of Cr(III) during the thermal treatment (combustion) of Cr(III)-containing materials. Although the extent of this transformation depends on factors such as temperature and the presence and concentration of other elements (e.g., Cl, S, H, alkali metals, Ca, etc.), as well as excess air [25], the exact form of Cr in ashes has been theoretically assessed based on the system's Gibbs free energy minimization. The potentially predominant compounds of Cr at different combustion temperatures were obtained from the literature and are presented in Table 5.

Cr is mostly found as Cr(III) in ashes obtained below 400 °C. At moderate combustion temperatures, Cr should predominantly be in its hexavalent form as $CrO_2(OH)_2$ (see Table 5). However, according to the literature, Cr(VI) constitutes only around 1 to 5 wt% of the total Cr content [27–30]. This is because the input fuel composition, as well as excess air, has a stronger influence on the Cr(VI) formation than the combustion temperature itself [25].

Table 5. Potentially predominant compounds and phases of chromium in oil shale ash at different temperatures [26]

100–400 °C	400–800 °C	800–1000 °C	Above 1000 °C
Cr_2O_3 (s)	Cr_2O_3 (s) → $CrO_2(OH)_2$ (g)	$CrO_2(OH)_2$ (g) → CrO(OH) (g)	CrO(OH) (g) → CrO_3 (g)

Abbreviations: s – solid, g – gas.

It is well-established knowledge that trace elements tend to concentrate in finer ash fractions. In the case of oil shale CFBC, Cr concentrations have been measured to range from 17 mg/kg in bottom ash to around 75 mg/kg in the last fields of electrostatic precipitators (ESPs) [14]. Notably, the average Cr content in soil in northeastern Estonia is around 31 mg/kg, with maximum concentrations exceeding 130 mg/kg, while the national average value is around 42 mg/kg [30]. In oil shale, Cr concentrations range from 15 to 38 mg/kg [31, 32]. For most trace elements, concentrations are typically higher in the finer ash fractions. This phenomenon is described by the so-called relative enrichment factors (RE), which describe the concentration of an element in a certain ash fraction relative to its concentration in the fuel [33]. For the trace elements examined in this study, including Cr, the RE values across different OSA fractions from the CFB boiler are presented in Figure 1.

Generally, the concentration of trace elements in different OSAs varies only slightly. In contrast, wood ashes show much wider variability: Cr can range from 11 to 9914 mg/kg, Zn from 100 to 12 100 mg/kg, Cu from 13 to 8793 mg/kg, Ni from 3 to 510 mg/kg, and Pb from 3 to 1900 mg/kg [34]. Table 6 gives a literature-based insight into the ranges of selected trace elements in ashes from typical Estonian tree species, compares them with those in oil shale, OSA from Estonian oil shale-fired CFBC boilers, and average Estonian soil, as well as includes comparisons with world reference plant ash and WWA. The concentrations of elements in the OSA from the current study (Table 2) fall within the ranges reported in the literature (Table 6), whereas the

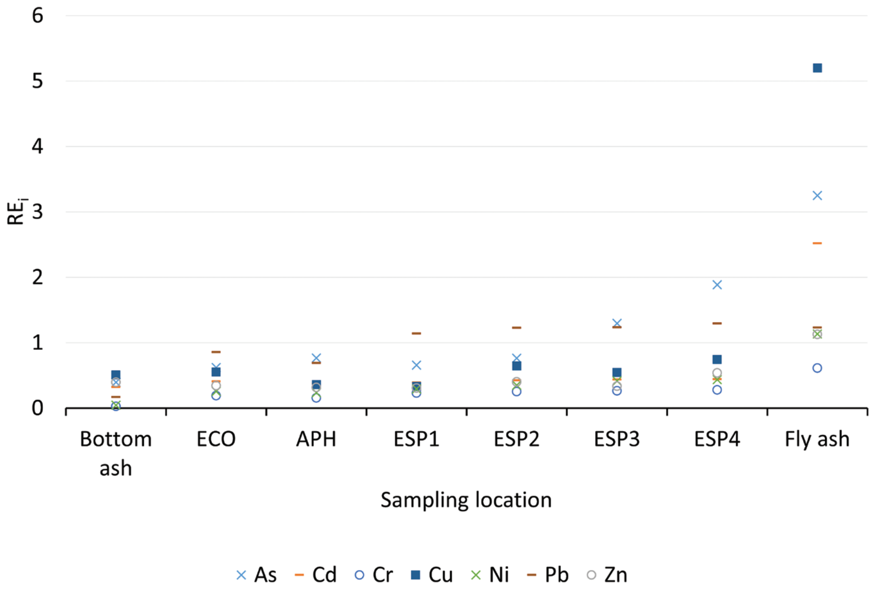

Fig. 1. Relative enrichment factors of selected trace elements in ash flows of an oil shale-fired CFBC unit.

concentrations of all investigated elements in WWA (Table 2) are significantly higher compared to those in the OSA and also exceed the WWA data reported in the literature (Table 6). For most trace elements investigated, the measured concentrations in WWA were within the limits previously reported for wood and bark ashes (Table 6).

Table 6. Ranges of contents of selected trace elements in the ashes of some typical Estonian tree species and their barks [35], oil shale [31, 32], oil shale ash [14], soil [30], world reference plant ash [36], and waste wood ash [37]

Element	**Oil shale** [31, 32], mg/kg$_{DW}$	**Oil shale ash** [14], mg/kg$_{DW}$	**Wood ash** [35], mg/kg$_{DW}$	**Bark ash** [35], mg/kg$_{DW}$	**Soil** [30], mg/kg$_{DW}$	**World reference plant ash** [36], mg/kg$_{DW}$	**Waste wood ash** [37], mg/kg$_{DW}$
As	7–21	<56.6	n.d.*	n.d.	n.d.	2.0	7.81
Cd	0.2–4	<2.4	n.d.	n.d.	0.4	1.0	2.45
Cr	15–38	<74.4	100	1200–7100	42	31	67.5
Cu	6–55	<15	70–330	180–1000	11	204	46.7
Ni	13–21	<42.2	30–100	570–3400	22	31	0.72
Pb	19–30	<124.7	80–470	10–170	16	20	43.2
Zn	27–84	<309.6	1700–4700	1600–11200	37	1020	3300

* n.d. – not determined.

3.2. Leaching of chromium

The mobility of trace and other (major) elements is determined by their solubility. However, not all soluble compounds are readily leachable, particularly those encapsulated within particles. Cr(VI) is considerably more soluble in water than Cr(III), leading to its significantly higher mobility. The mobility of Cr to water is a complex process, influenced by several factors, such as pH, the presence of competing cations or anions, dissolved organic matter, and the L/S mass ratio [38]. According to the literature, the enhanced mobility of Cr(VI) is typically observed in waters with a pH greater than 7, especially in alkaline environments with a pH between 8.5 and 12 [39].

The leaching experiments aimed to investigate the release of Cr from OSA samples collected from Baltic Power Plant, along with samples of CW from the ash removal system, and WWA. These leaching tests were conducted without pH adjustment. In the current study, the initial pH of CW was about

12.3 (see Table 3) and increased to approximately 12.8 over the course of the 24-hour leaching test. The effects of the leachant type (CW or DW) and the L/S ratio on Cr leaching were evaluated. Although the data are somewhat scattered (Fig. 2), it is evident that the L/S (CW/ash) ratio influences Cr leaching. A higher L/S ratio increases the leaching driving force (concentration difference), which subsequently promotes greater Cr release. It is noteworthy that Cr leaches more readily from WWA, accounting for 6–10% of the total Cr, in contrast to OSA, which contributes only 1–5%. At an L/S ratio of 20, the Cr concentration in CW/OSA and DW/OSA leachates increased by 144 µg/L and 155 µg/L, respectively.

Although the mass fractions of Cr leached from the WWA and OSA + WWA mixes are similar, significant differences in Cr concentrations in water occur at varying CW/ash ratios. For instance, a CW/WWA ratio of 16 resulted in a Cr concentration increase of 780 µg/L, whereas a CW ratio of 50 for a 90% OSA / 10% WWA mixture led to an increase of only 90 µg/L. In contrast, when leaching Cr from OSA with CW, the Cr concentration increased by no more than 47 µg/L. On one hand, this outcome is quite expected and caused by the additional leaching of Cr from the OSA sample. At the same time, it is known from the literature that OSA can bind Cr [40]. Similar findings have been reported for bituminous coal ash, where leaching tests showed a significant reduction in Cr(VI) levels after the ash was exposed to water: approximately 60% of the Cr(VI) leached into water, 20% was reduced to Cr(III) and retained in the ash, while 20% remained as Cr(VI) in the ash [41].

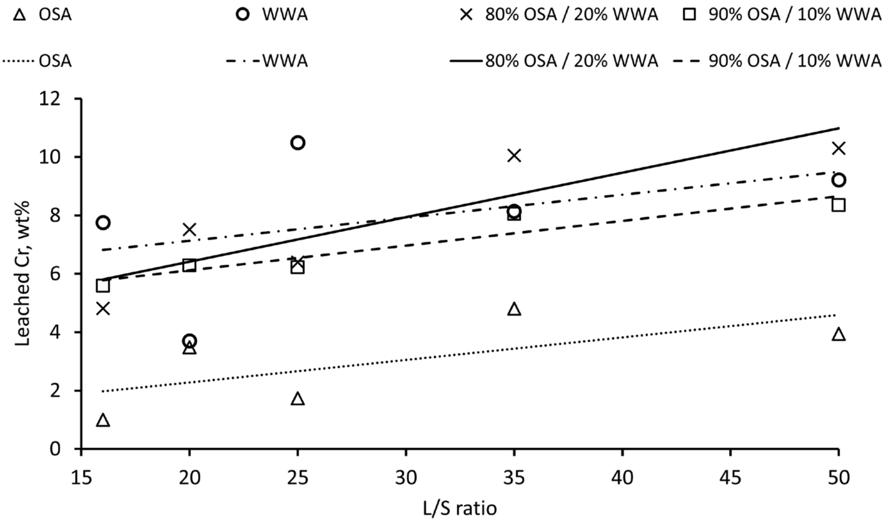

Fig. 2. Dependence of the mass fraction of Cr leached from ashes on the L/S ratio. Symbols represent different ashes. Lines show trends for each ash type.

The analysis of CW indicates that over 90% of the Cr is present as Cr(VI), which is consistent with literature data [18]. In the current study, an experiment also confirmed the low solubility of Cr(III) in DW. When pure $Cr(OH)_3$ was leached in DW at an L/S ratio of 25, the Cr concentration in the leachate was measured to be 8 µg/L at a pH of 7 after 24 h of shaking. According to the literature, the solubility of Cr is significantly enhanced also in the presence of cations or anions to form soluble chromates [42, 43]. To confirm this, a sufficient amount of $Cr(OH)_3$ (approximately 40 g/L) was added to the Cr-free saturated $Ca(OH)_2$ solution (L/S = 25), resulting in a Cr concentration of 114 µg/L at a pH of about 12.5. This experiment was then repeated with $Cr(OH)_3$ added to CW (L/S = 25). After 24 hours, the Cr concentration measured was 1695 µg/L, indicating that the composition of the used leachant significantly enhances Cr solubility.

At the same time, the selection of leachant, either CW or DW, had a minimal effect on Cr leachability from OSA. For instance, at an L/S ratio of 20, the Cr concentration increased by 50 µg/L with CW and 76 µg/L with DW. This indicates that most of the Cr in OSA is insoluble under the applied leaching conditions.

3.3. Leaching of selected trace elements from OSA and WWA mixture

In addition to Cr, the leachability of other trace elements from the 90% OSA / 10% WWA ash mixture (Fig. 3) was investigated as a function of the L/S ratio. Similarly to Cr, the amount of each element leached per unit mass of ash generally increased with rising L/S ratio (except in the case of Ni). Studies have also shown that the leachable amount of trace elements generally increases by increasing the L/S ratio; for example, the release of Cr(VI) reaches a plateau at an L/S ratio of 100 L/kg [44–46].

Among the elements studied, Cu was the most mobile, with up to 3.1% of its content in the ash leached within 24 hours (Fig. 3a). Less than 1.5% of the total content in the ash was leached for Ni, Cu, As, and Pb (Fig. 3a), and less than 0.3% for Zn and Cd (Fig. 3b). However, the concentrations of the studied trace elements in the water generally remained below 50 µg/L, regardless of the L/S ratio, even though Cu, Zn, and Pb concentrations in the ash were several times higher than that of Cr. This could be due to the highly alkaline environment promoting the formation of metal hydroxides for some elements, which could potentially restrict the dispersion of these trace elements. For example, Fedje et al. [47] observed that at elevated pH levels, Pb forms complexes such as and that decrease the solubility of Pb. The decreased leachability of several elements (Cd, Zn, Ni, Cu) at pH values exceeding 10, compared to those below 7, has been reported in the literature for both municipal solid waste incineration air pollution control wastes [48] and soil and fly ash mixtures [49]. Nonetheless, in addition to chemical speciation, the leachability of trace elements is also affected by other factors, such as the ash matrix and the location of the trace elements on ash particles.

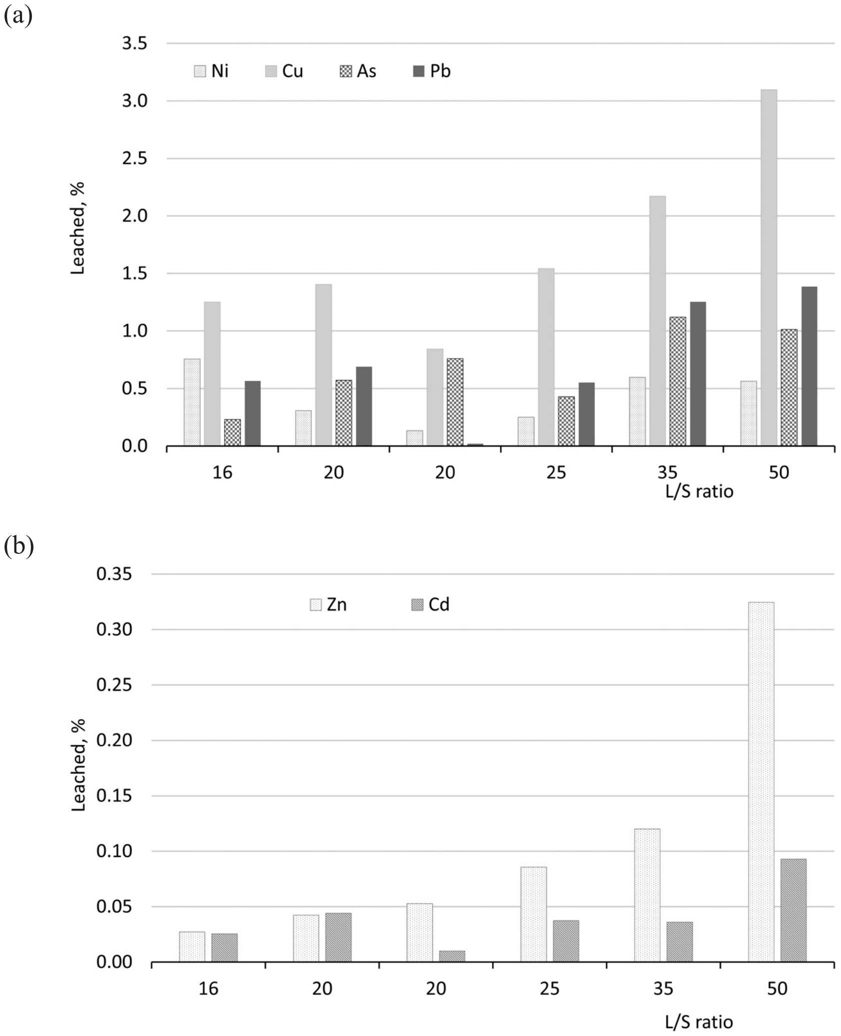

Fig. 3. Impact of L/S ratio on selected trace element mobility in a 90% OSA / 10% WWA mixture.

It is important to note that the leaching behavior varies between elements in terms of concentration. As the L/S ratio rises, the leachability or release of most elements also tends to increase (Fig. 3). However, as shown in Figure 4, the Cr concentration in the leachate decreases, while the Zn concentration increases with rising L/S ratio. For other elements, the concentration in the leachant either follows a pattern similar to Cr or remains nearly unchanged. This suggests that the maximum leachable amount of Cr is reached already at an L/S ratio of 10, whereas Zn release appears to be controlled by its solubility in the leachate water.

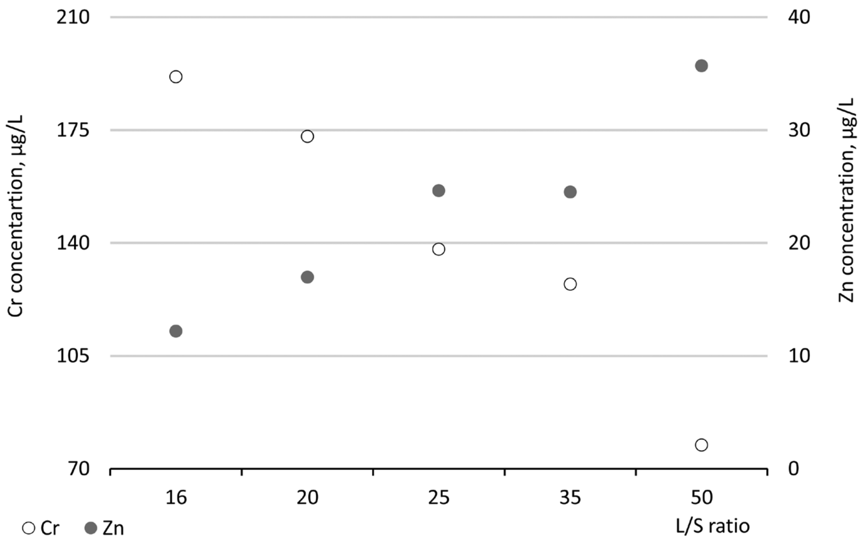

Fig. 4. Concentration of Cr and Zn in leachate (µg/L) as a function of L/S ratio.

Table 7 presents the mobility of selected trace elements from OSA and WWA determined in this work, along with a comparison to literature data. The results of the current work are based on leaching tests with ash field CW, in comparison with literature results conducted with distilled water. As can be seen from Table 7, the concentration of Cr in virgin wood incineration ash (Type II pellet ash) and its mobility to the aqueous environment is, according to the literature, several times higher compared to oil shale combustion ashes.

The results of the current study indicate that, generally, the leachable amount of trace elements increases with higher WWA content in the ash mixture; however, the leachability of Cu and Cd decreases as the content of WWA increases. Although the relative mobility of Cr from both OSA and WWA is approximately the same, the initial concentration of Cr in WWA is several times higher than in OSA (Table 7).

Among the elements studied, Cr is one of the most mobile in OSA, and according to the analysis (see Table 3), 90% of Cr is in the form of Cr(VI). In contrast, Cr leached from WWA was mainly in the form of Cr(III), and its mobility in alkaline water saturated with $Ca(OH)_2$ increased by over 15 times compared to its mobility in distilled water. When using CW as a leachant, the mobility of Cr increased by over 200 times, indicating that the composition of the leachant strongly enhances the solubility of Cr(III).

Table 7. Mobility of selected trace elements from wood ashes (including waste wood ash) and oil shale ashes with a comparison to literature data

Element	**OSA** **(current study)**		**WWA** **(current study)**		**Oil shale solid heat carrier ash** [50]		**Type II pellet ash*** [51]		**Oil shale CFBC bottom ash** [16]	
	Ash, mg/kg	**Leached, %** (L/S = 20)	**Ash, mg/kg**	**Leached, %** (L/S = 20)	**Ash, mg/kg**	**Leached, %** (L/S = 10)	**Ash, mg/kg**	**Leached, %** (L/S = 10)	**Ash, mg/kg**	**Leached, %** (L/S = 10)
As	10.0	0.70	13.7	0.25	8	0.75	41	0.01	n.a.**	n.a.
Cd	3.24	0.04	8.22	0.01	<0.1	n.a.	<0.5	n.a.	0.1	0.20
Cr	29.7	3.82	269	3.69	22.5	0.18	280	8.93	20	0.10
Cu	9.89	5.00	400	0.31	10.6	0.28	609	0.00	8	0.04
Ni	17.6	0.38	65.2	–***	18	0.11	68	0.15	21	0.01
Pb	28.9	0.42	513	0.94	36	n.a.	835	0.01	24	0.02
Zn	79.7	0.09	6409	0.42	43	0.33	1986	0.10	41	0.02

* 75% lignocellulosic residues + 25% furniture manufacturing residues.
** – n.a. – not analyzed.
*** below the level of detection.

4. Conclusions

Based on the results of the current study, it can be concluded that, in general, the mobility of trace elements increases as the content of WWA in the ash mixture increases. Among the trace elements studied, Cr is one of the most mobile elements in both oil shale ash (OSA) and waste wood ash (WWA), with 3.82% and 3.69% of Cr leached at an L/S ratio of 20 over 24 hours, respectively. Since WWA contains more than ten times the amount of Cr compared to OSA, the absolute leachable amount of Cr from WWA to the aqueous environment is several times higher than that from OSA.

The concentration of Cr in the circulating water of the oil shale power plant, used as a leachant, was 86.5 µg/L, with more than 90% present as highly soluble and toxic Cr(VI). Leaching of Cr from waste wood fuel ash could lead to much higher concentrations in the circulating water (up to 850 µg/L on average). It should be noted that the exact concentration is highly dependent on the Cr content in the fuel. However, although using waste or demolition wood may seem appealing, it is crucial to proceed with caution, as this could result in serious environmental consequences in the future. The exact levels of Cr and other trace elements in the circulating water also depend on other factors, such as precipitation/evaporation and the production capacity of the power plant. Further studies will address these issues.

Data availability statement

Data will be made available upon request.

Acknowledgments

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