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RESEARCH AND ANALYSIS

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International comparison of impurities mixing and accumulation in steel scrap

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Abstract

The accumulation of impurities in the recycling of steel impacts the quality of secondary steel. Understanding impurity levels is crucial in the context of the proliferation of circular economy policies, expected high recycling rates, and growth of scrap consumption. By assuming the accumulation of impurities to be equal worldwide, the understanding of the extent and variation of the mixing and accumulation was limited in previous studies, and the factors influencing those variations were not considered. This is a first cross-national comparison of impurity accumulation in recycled steel. In this study, the copper, tin, nickel, chromium, and molybdenum content was analyzed in over 500 samples of electric arc furnace rebars from China, Japan, Vietnam, Ukraine, and the Netherlands (representing northwestern Europe) with an optical emission spectrometer. The impurity content in rebars represents the content of impurities accumulated in steel scrap in the countries studied. The measured content of impurities was then used to determine the factors influencing the accumulation of those impurities. It was revealed that the recycling technology, the presence of a market for recovered metals, the quality of the material input, steelmaking practices, and the management of byproducts derived from a legislative or economic context played a role in the impurities content. By communicating on scrap chemical content, the collaboration between the recycling and steel industries could be enhanced in terms of matching the demand and supply and facilitating an increase in the scrap share in steelmaking.

KEYWORDS
industrial ecology, materials management, recycling, scrap, steel, tramp metal

1 INTRODUCTION

Material industries are associated with intensive energy consumption and important greenhouse gases (GHGs) emissions. Specifically, the global production of iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminum was estimated to be 20% of final energy consumption in 2017, representing more than half of the energy consumed by industry (IEA, 2019). In addition, the share of direct CO_2 emissions from material production grew from 11% to 20% between 1990 and 2017 (IEA, 2019). In 2019, it was reported that the iron and steel industry accounted for 7% of global CO_2 emissions (IEA, 2020). Material recycling plays a significant role in the reduction of energy consumption, the mitigation of emissions, and in improving resource efficiency. The global share of steel produced by the lower energy-intensive electric arc furnace (EAF) is growing (Worldsteel, 2020). Based on the historical increase in steel consumption, the generation of scrap is also expected to increase over time (Pauliuk et al., 2013; UNEP, 2019; Voet et al., 2019). Therefore, the consumption of steel scrap is also expected to be increased, which warrants a close examination of scrap quality.

Steel contains both intentionally and unintentionally introduced elements. Alloying elements, like chromium (Cr), nickel (Ni), molybdenum (Mo), manganese (Mn), and vanadium (V), are intentionally chemically introduced to ensure specific properties, notably in high-strength and stainless steel. Coating elements, like zinc (Zn), aluminum (Al), Cr, and Ni are intentionally applied to provide corrosion resistance. Unintentionally introduced elements result from the incomplete dismantling and material separation during recycling, often due to the complexity of the materials mixed in modern products.

While some elements (Si, Mn, etc.) are oxidized to slag during the refining of scrap, others remain in the molten steel. The technologies developed to eliminate these so-called tramp elements from molten steel have been reviewed (Daehn et al., 2019; Zhang et al., 2019), but their application in current metallurgical processes is limited. In particular, Cu, Sn, Ni, and Mo present challenges for steelmaking (Nakajima et al., 2011; UNEP, 2013). Both intentionally added alloying elements and unintentionally introduced elements are recognized as impurities. While some of these impurities are introduced from the ore and fluxing agents, scrap is the main source (Daigo et al., 2017). In Japan, two-thirds of Cu accumulation has been attributed to insufficient scrap separation and one-third is from alloying elements (Daigo et al., 2017).

The repeated recycling over time results in the accumulation of tramp elements. This accumulation is recognized to have a negative impact on the quality of recycled steel and is expected to result in restrictions on recycling in the future (Daehn et al., 2017). The relationship between the impurities content in scrap and the tolerance of steel product end-use sectors to these impurities has been studied by a material flow analysis (MFA). The focus has been mostly on the Cu content, since Cu accumulation over recycling iterations is considered a matter of major concern (Cooper et al., 2020; Daehn et al., 2017; Daigo, et al., 2005). The total content of Cu, Sn, Cr, Ni, and Mo is also used to study the accumulation/tolerance relationship (Dworak & Fellner, 2021). While these MFA studies serve as a warning of the likelihood of accumulation of tramp elements, knowledge of the impact of these tramp elements on steel properties is limited. Even if a high content of tramp elements is considered acceptable in terms of properties, controlling the microstructures would become challenging. Recently, the impact of 15 impurities on main steel properties, including the tensile strength, elongation, yield point, soundness in the welding area, and fracture toughness, was overviewed by Daigo et al. (2020).

One of the most compelling reasons for the focus on Cu accumulation in many studies is the surface hot shortness that occurs during the rolling process (Shibata et al., 2002). Daehn et al. show that globally over the long term, the expected levels of Cu contamination reached would require the recycled steel to be used exclusively in products with a higher Cu tolerance (e.g., reinforcing bars), and that the demand for this scrap will be lower than the supply, assuming that scrap is freely traded for optimal recycling (Daehn et al., 2017). In Europe, this has already been reported to be the case: since 2009, the supply of scrap with higher content of tramp elements has exceeded its demand, with the remnant quantity exported (Dworak & Fellner, 2021).

To maintain the quality of steel and to keep the tramp elements content below tolerable limits, secondary steel is diluted with primary materials or manufacturing scrap. Because of its impurity tolerance, EAF steel tends to be used to produce long products, but EAF can also be used for flat products provided the input quality is ensured through dilution (Arens et al., 2017; Nakamura et al., 2012; Zhu et al., 2019). It has been argued that international trade could contribute to the optimized distribution and use of scrap (research and analysis). Developed countries mostly produce high-quality steel, which requires low-impurity input, and domestically generated scrap may therefore not satisfy impurity tolerance level without dilution (Dworak & Fellner, 2021; Zhu et al., 2019). Noro et al. (1997) showed that the accumulation of scrap within countries is highly unlikely, because of the demand in other countries. The trend is for developed countries to export scrap to developing countries, where steel consumption is driven by urbanization, which is accompanied by a demand for materials with less stringent quality requirements (Michida et al., 2011). Because these countries typically do not generate sufficient obsolete scrap, they import low-quality scrap. It has been pointed out, however, that international trade is not a long-term solution to impurities accumulation, and its use to address the problem of impurities tolerance is therefore limited (Daehn et al., 2017).

The dependency of the quality of EAF steel on the quality of the scrap highlights the importance of defining the status quo regarding the accumulation of tramp elements in scrap. The same impurity content was assumed globally in MFAs on the accumulation of tramp elements, likely due to a lack of actual country-level data. However, the accumulation of tramp elements in scrap was approximated by measuring their content in remelted shredder scrap in Japan (Toi et al., 1997), and the accumulation in steel was determined by measuring the impurities content in reinforcing steel bars in Japan and China (Daigo et al., 2017; Daigo & Goto, 2015).

To address the issue of limited measurements of tramp elements accumulation and contribute to the knowledge of the geographical disparity, the aim of this study is to provide a cross-country comparison of impurity mixing in steel scrap. Based on the results, the impact of local recycling system on tramp elements accumulation and the implications for industry are discussed.

2 | RESEARCH METHOD

2.1 | Research design

Due to the difficulty of directly observing the mixing and accumulation of impurities in steel scrap during recycling, the present study approximates them by measuring the impurity content of steel produced in secondary steelmaking. The content of tramp elements in steel is impacted not only by inefficient separation, but also by country-specific patterns of steel production and trade. The steelmaking process, the steel product type (long/flat), and the grade of the steel influence the proportion between primary and secondary input, the type of scrap input (new/old) and, consequently, the impurity input. Trade patterns determine the share of locally produced products and scrap in the consumption and therefore impact the country-specific accumulation of impurities. Finally, the separation, sorting, and recovery affect the quantity and type of the remaining elements. Thus, by focusing on country-specific cumulative process, this study is designed to exclude most of the factors deemed to be a source of dilution and those which originate outside the studied territory. Reinforcing bars were chosen as the representative study object because of their highest tolerance to Cu content and a higher content of impurities than found in other steel products (Daigo et al., 2017). To exclude the effect of dilution, it is assumed that manufacturers of rebars prioritize cheap old scrap input, avoiding pig iron, direct-reduced iron (DRI), and new scrap consumption when impurity content is below the tolerance level.

The methodology for identifying which countries are suitable for this study of country-specific tramp elements mixing and accumulation is explained further. The acquisition of samples reflecting country-specific steelmaking condition, and associated data collection, validation, and analysis are also explained.

2.2 | Analysis of the representativeness of country-specific production and accumulation

To ensure the collected samples represent the country-specific production and accumulation, it was necessary to verify whether the samples are produced in the country and determine the origin of the scrap used for their production. Country-specific production was verified by the ratio between the steel bar import and consumption. Bars with a 10% or less share of imports were considered to be produced in the country. In cases where the ratio was higher than 10%, the rebar import flows were studied to check for the presence of a trade cluster. Production representativeness also impacts the sampling procedure, as described in the next section. Country-specific mixing and accumulation was verified by the ratio between scrap import and consumption. For a ratio of 10% or less, the share of imported scrap in total scrap consumption was considered negligible. Because the rebar samples were produced from locally generated scrap, it was assumed they were representative of local recycling conditions. When the ratio was higher than 10%, then the percentage of locally generated and imported scrap was investigated, as well as the origin of imported scrap and presence of a trade cluster. When a similar trade cluster was identified for bars and scrap, the territory was also considered representative for area-specific production and accumulation.

The choice of countries with country-specific production and impurity accumulation was based on statistical data from Worldsteel, and the United Nations International Trade Statistics Database (UN Comtrade). Worldsteel provides data on the production and trade of crude steel, pig iron and DRI, as well as steel bars production, and UN Comtrade provides data on the trade of scrap and steel bars. First, of the 41 countries producing rebars, 16 were considered to have representative production and/or accumulation patterns. Samples were collected in three of them: China, Japan, and Ukraine. The analysis shows that the consumption of scrap is almost exclusively local: the collected samples were therefore considered representative for country-specific accumulation.

Vietnam is not reported in statistics of rebar production despite the presence of this industry. In Vietnam, local scrap (52%) is mixed with scrap imported from developed and developing countries (24% from each). However, the imported scrap is hand sorted, with the copper and aluminum separated before melting. Thus, the consumed scrap is representative of local quality, and samples were also collected in this country.

Finally, a trade cluster of rebars and scrap in Europe is identified within five countries: the Netherlands, Germany, Belgium, France, and the United Kingdom. While the Netherlands is not reported as a rebars producer, around 90% of bars were imported from one of these countries during the period 2010–2015. The consumed scrap also originated mostly from the region. Therefore, the five countries were considered one region of Western Europe in this study, and the collected samples were considered representative. A detailed analysis is provided in the supporting information along with the relevant data (Supporting Information S1 and S2). Countries chosen for this study provide insight into the variability of recycling and waste management systems at different stages of economic development: Japan and Western Europe are developed economies, Ukraine is an economy in transition, while China and Vietnam are developing countries (UN, 2015).

TABLE 1 Description of sampling sites and sample size

Country	Collection site	Sample type	Year	Number of collected samples	Number of EAF samples	Number of samples and elements below detection limit
China	Scrap yards and construction sites	Old scrap	2012–2013	26	22	5 Sn, 5Mo
	Scrap yard	New scrap	2016	124	19	2 Sn, 15 Mo
Japan	Scrap yard	New and old scrap	2015	100	89	1 Mo
The Netherlands	Scrap yard	Old scrap	2015	75	65	1 Mo
	Bar retailing company	New rebar	2017	115	114	2 Ni, 8 Mo, 2 Sn
Vietnam	Scrap-based steelmaking	New rebar	2015	121	121	4 Mo
Ukraine	Scrap-based steelmaking	New rebar	2015	98	98	–

2.3 | Sampling and instrumental analysis

The sampling procedure should infer a representative set for the diversity of rebars produced in the country around the same period. For countries with locally representative production, a scrap yard was the preferred sampling site because it contains a mix produced by various steel companies. However, it is difficult to define the production process for samples collected at these sites. Sampling at steelmaking sites was preferred in countries with a high share of imported bars to ensure the samples reflected local conditions. However, despite being able to obtain reliable knowledge of the production process and ensure similar production year, steelmaking sites can be limited as sampling sites based on the variability of grades and material input. With these points in mind, a higher number of producers provide better variability. While sampling from construction sites or a retailing company can provide variability from different steelmaking companies, this needs to be ensured. Based on the analysis of country-specific production, samples were collected from scrap yards, construction sites, retailing companies, and from secondary steelmaking sites. In each country, rebars were collected randomly, with no regard to size, grade, or heat to avoid bias.

In a previous study, it was shown that 200 samples ensured a representative distribution of Cu content of 0.269 (Daigo et al., 2017), whereas a sample size of around 100 resulted in similar average Cu content of 0.278 (Daigo & Goto, 2015). Thus, 100 samples were considered sufficient to represent the distribution of impurities.

The sites and the number of gathered samples per country are listed in Table 1. Because Japan and China are local producers, the samples were collected from scrap yards. An analysis of the Japanese samples has been published (Daigo & Goto, 2015). However, data from the 200 samples (Daigo et al., 2017) is not included in this study since the steelmaking processes were not distinguished during sampling. Samples from Ukraine and Vietnam were collected from steelmaking companies to avoid the impact of imported rebars. The samples are new rebars produced by EAF companies and electromagnetic induction, fed by scrap, respectively. Even though it was considered more appropriate to collect samples directly from producers in Western Europe, they were also collected from scrap yards because of the difficulty of doing so. In China and the Netherlands, two sampling campaigns were conducted. Samples from China and the Netherlands represent a mix of postconsumer scrap collected from scrap yards and new rebars collected from construction sites and a bar retailing company.

To prepare samples for analysis of impurity contents, a cross-sectional surface grinding was done by a sand belt. A spark-discharge optical emission spectrometer (Spark-OES, ARL4460, Thermofisher Scientific Inc.) was used to measure the elemental composition. All measurements were performed using the small sample mode, which allowed the quantitative determination of rod-like samples with diameters down to 3 mm. The limit of detection for elemental Cu is 0.01%, 0.003% for Sn and Mo, and 0.02% for Cr and Ni. Each sample was measured three times to obtain a representative average value and to reduce the measurement error.

2.4 | Data analysis

Random sampling from scrap yards results in rebars produced by a basic oxygen furnace (BOF) and EAF. To distinguish between them, in previous studies a maximum threshold for Cu content was set in for the BOF (0.03% or 0.05%) and a minimum value was set for EAF steel (0.05% or 0.11%) (Daigo & Goto, 2015; Toi et al., 1997). This study defines country-specific thresholds for secondary steel based on the relative frequency distribution of the Cu content. When measured data contain BOF and EAF samples, the crossing point of bimodal distribution was expected to be observed and secondary steel threshold can be determined. For four countries, a minimal Cu content for secondary steel of 0.05% was applied, based on country-specific relative frequency distributions for measured Cu content provided in Supporting Information S1. This is in good agreement with values in the literature (Daigo & Goto, 2015; Toi et al., 1997). In samples from China, no bimodal distribution was observed: that is, the Cu content of

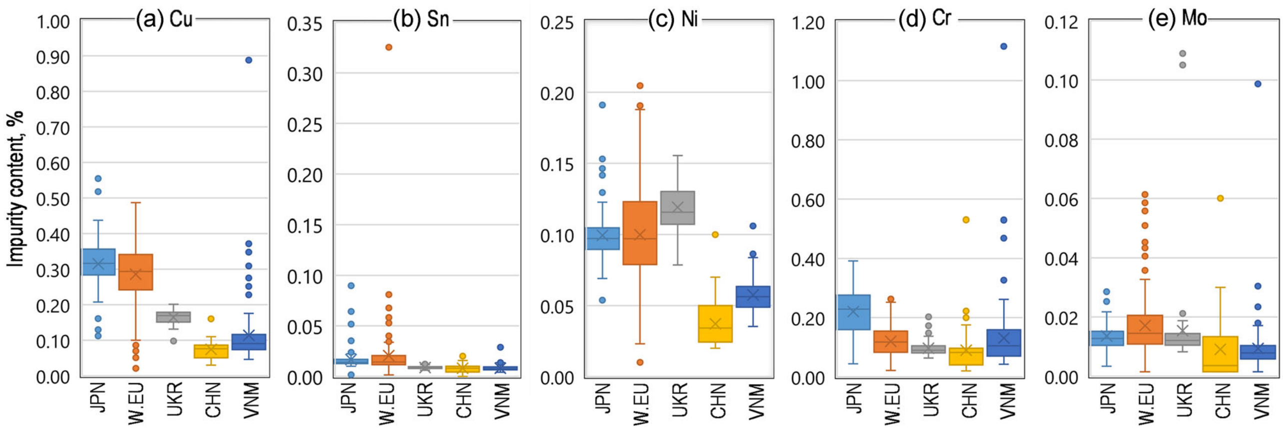

FIGURE 1 Distributions of the elemental analysis of (a) Cu, (b) Sn, (c) Ni, (d) Cr, and (e) Mo in Japan (JPN), W. Europe (W.EU), Ukraine (UKR), China (CHN), and Vietnam (VNM). Associated data are available in Supporting Information S2

TABLE 2 Comparison of 90% data ranges and maximum values with carbon steel/alloy steel boundary and standards for reinforcement bars

	5th percentile limit (%)	95th percentile limit (%)	Maximum values (%)	Carbon/alloy steel boundary (ISO)
Cu	0.058	0.385	0.89	0.4
Sn	0.005	0.034	0.33	Not defined
Ni	0.032	0.149	0.20	0.3
Cr	0.040	0.277	1.12	0.3
Mo	0.002	0.030	0.11	0.08

46% of the samples ranged between 0.02% and 0.03%. Considering that the share of scrap input in EAF is comparatively low in China (550–600 kg per tonne), and old scrap represents 35% of the total scrap consumption in 2015 (McKinsey & Company, 2017), a lower Cu content threshold for secondary steel was set at 0.03%. The number of representative samples is provided in Table 1.

The samples collected in China, Japan, and the Netherlands included newly generated rebar scrap and postconsumer rebars, distinguished by appearance. According to the Japanese EAF steel association, the time gap does not impact the average Cu content: the impurity content of steel bars was reported to fluctuate between 0.28% and 0.31% over a long period of time (Daigo et al., 2017). The average Cu content in new rebars and old scrap samples from the Netherlands (0.29% and 0.28%, respectively) and China (0.07% and 0.08%) was similar. The difference between old and new samples was not further addressed in this study, and samples were treated together.

It is acknowledged that the values of the impurity content may have been below the detection limit (DL) in some cases (Table 1). From a statistical perspective, the impurity contents could have been between zero and the detection limit. The Mo and Sn contents were mostly considered to be below the DL. A substitution with half the DL was employed for all values below the DL assuming a uniform distribution between zero and the DL. Since their proportion was small in samples from Japan, the Netherlands, and Vietnam, this substitution did not result in substantial bias. In the case of the Chinese samples, the substitution altered the mean results and the variance of Mo and Sn.

3 | RESULTS AND DISCUSSION

3.1 | Statistical data analysis of impurity contents

The measured impurity contents indicated that the mean value is greater than the median in most cases, meaning the distribution was skewed to the right. However, the distribution was skewed to the left in four cases: Cu content in samples from Japan, Western Europe, and Ukraine and Cr content in the Japanese samples. For a skewed distribution, quartiles provide a better description of the asymmetry than normal distribution. The distributions of the obtained elemental analysis of Cu, Sn, Cr, Ni, and Mo in different countries are illustrated in Figure 1. Associated data are provided in a numerical format (Supporting Information S2).

Among the 528 measured values for each element, 90% fell between values of 5th and 95th percentiles, shown in Table 2. The values of 95th percentile were lower than the maximum content of elements in the carbon steel/alloy steel boundary defined by the International Standard Organization (ISO), confirming that the collected samples were carbon steel.

The maximum measured values, provided in Table 2, were also the highest outliers in Figure 1. It was necessary to determine whether these outliers were true outliers, for example, sampling and analytical errors, transcription errors or data-coding error (Zhang, 2007) or are they representative of a variation range of impurity contents. Two types of standards were considered to rule out these possibilities: the standard defining the boundary values between carbon steel and alloy steels, and the standards for the allowable content of impurities in concrete rebar. It was found that the maximum measured values for Cu, Cr, and Mo exceeded the carbon/alloy steel boundary values. The standards for rebars (International Standard ISO 6935-2, European 10080:2005 [DSTU EN 10080:2009 in Ukraine], Japanese JIS G3112 2010, Chinese GB/T 1499.2 2018, and Vietnamese TCVN 1651-2 2018) provide maximum content of C, Si, Mn, P, S, and carbon equivalent. Only the European standard requires a limit of 0.80% for the Cu content. From this perspective, the maximum measured value of 0.89% can be considered realistic. The highest Cr value was for the Vietnamese samples: these were collected from a small-scale secondary-steel production site, which is not likely to have a quality-monitoring system. In this context, the measured value may be considered realistic. The highest measured Mo content exceeded the carbon/alloy steel boundary values by 27% and was also assumed to be realistic. Because the Sn content is not prescribed in the standards, it was assumed that maximum measured values are representative of carbon steel. It is concluded that the data which appear as outliers in Figure 1 are not true outliers, but correspond to mathematical outliers, and reflect the inherent variability in the content of impurities in steel.

3.2 | Country-specific impurity contents

As shown in the research design, the content of impurities reflects the extent of impurity mixing and accumulation in steel scrap. An analysis of the separation and recycling conditions in different countries was conducted to determine their impact on the mixing of tramp elements in steel scrap and to identify related factors. The impurity contents are compared as a function of Gross Domestic Product (GDP) at purchasing power parity (PPP) per capita, as reported annually by the World Bank. Median values of impurity contents were used due to the asymmetrical nature of the data and because medians are not impacted by extreme values. The GDP(PPP) average for the period 2012–2016 was used to be consistent with the years represented by the sample collection. A correlation was found between tramp element accumulation and economic growth, especially for Cu and Sn, as shown in Figure 2a–e. Underlying data are available in Table S2 of Supporting Information S1. In this section, this correlation is considered in detail, and explanations are provided of observed deviations.

Samples from high-income Japan and Western Europe have similar levels of accumulation for all investigated tramp elements, with the exception of Cr. In Japan, Cu content was 0.32%, and in Western Europe, it was 0.29%, as shown in Figure 2a. The Cu content of Japanese samples was above the content reported for shredded automobile steel scrap in Japan, which was reported to be 0.27% (Nakamura et al., 2012), but is lower than the Cu content in municipal waste, which is the most polluted type of scrap (reported as 0.37% for Switzerland) (Haupt et al., 2017).

The main sources of copper contamination are automotive scrap, waste electric and electronic equipment (WEEE) and demolition waste. During shredding, Cu is mixed with cut metal scrap and is difficult to separate, unless it is done manually (Daehn et al., 2019). This scrap is not fully separated from copper parts in electric motor and electrical wires. Another Cu source is scrap with a high Cu content, like rebars and stainless steel (Savov et al., 2003). Because information on the type of consumed scrap in all investigated countries was not available, the variation of the Cu content between countries was considered only in terms of the separation practices during recycling.

It has been reported that most of the material separation in Western Europe and Japan is done by shredding and mechanical sorting (Daigo & Goto, 2015; Kojima, 2018). While shredded scrap in European countries is composed predominantly of vehicles, home appliances, and household scrap, the breakdown of the scrap input to EAF is unknown. In Japan, end-of-life vehicles (ELVs) and home appliances are shredded separately, and the share of shredded scrap has been reported to account for 8% of total scrap consumption in 2015 (Japan Ferrous Raw Materials Association, 2015). To determine the impact of different impurity sources, information on the origin of the consumed scrap is essential.

The highest accumulation values of Sn were observed in Western Europe and Japan, both at 0.014% (Figure 2b). One of the sources of Sn is Sn-coated copper wires and Sn-based electronic solders, which contain 60–96% of Sn (Gordon et al., 2006). Thus, Sn is connected to either steel or Cu. Thus, it is not surprising that the trends for these two elements are similar with respect to economic development. Another source of Sn is tinplate scrap (0.2–0.8% of Sn): tinplate is used in packaging and recovered from household waste (Savov et al., 2003). While high steel packaging recycling rates were reported in Japan, European countries, and China for 2007 (Yellishetty et al., 2011), this does not contribute to the understanding of Sn accumulation results. Moreover, it was not possible to clarify whether the packaging is recycled in a closed loop (since European scrap specification states that all scrap grades must be free of Sn [EFR, 2007]). Likewise, no data were available regarding the share of packaging in the EAF input or the use of tin-free steel in packaging.

The median contents of Ni, Cr, and Mo are illustrated in Figure 2c–e, respectively. The median Ni content in Western Europe and Japan was 0.097%, and the Mo content was 0.014% and 0.013%, respectively. At 0.23%, the Cr content in Japan was almost twice that found for the other countries in the study (e.g., 0.12% in Europe). Common nickel-containing austenitic alloys are used in the transport and process industries, in "high-end" buildings, in appliances, and also in high-tech industries (Gordon et al., 2006). Cr-containing alloys and stainless steel are mostly used in household appliances, transportation, buildings, and infrastructure (Nuss et al., 2014). Mo is used in high-quality steel and in stainless steel in various sectors (automotive, aerospace, energy) (Miranda et al., 2019). In general, the accumulation of alloying elements is higher in developed

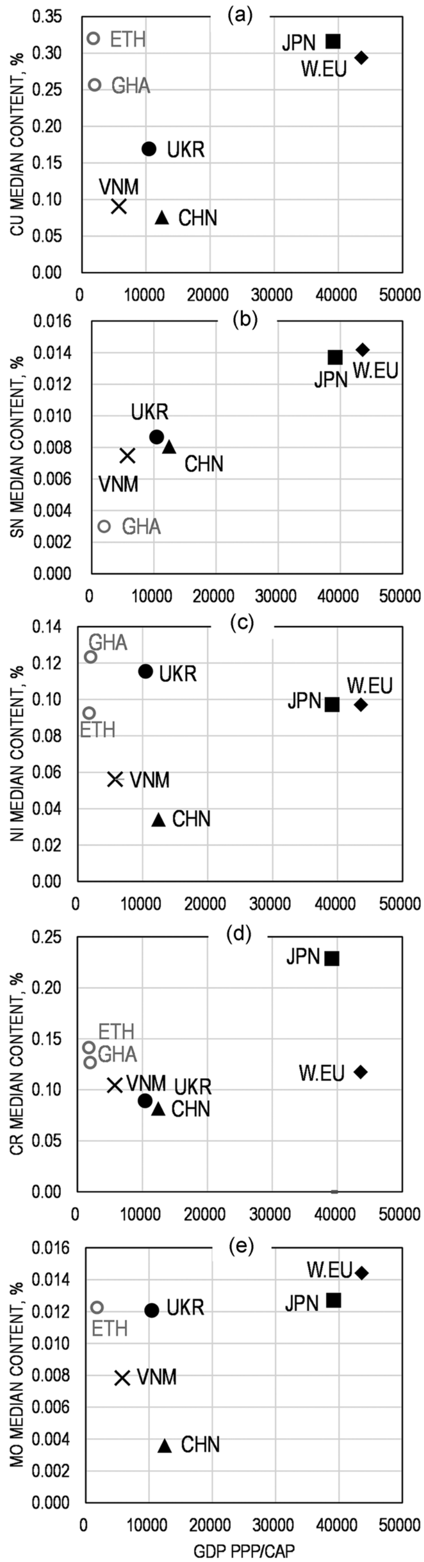

FIGURE 2 Relationship between median content of (a) Cu, (b) Sn, (c) Ni, (d) Cr, and (e) Mo, and average GDP (PPP) in Japan (JPN), W. Europe (W.EU), Ukraine (UKR), China (CHN), and Vietnam (VNM). Associated data are available in Table S2 of Supporting Information S1

countries. While this probably reflects country-specific consumption patterns, further specific investigation is needed to confirm this assumption. The high Cr content in Japanese scrap can be attributed to steel production practices rather than to alloy consumption patterns. Due to the limited space for landfill in Japan, steelmaking slag is often used as a bedding material in road construction, which has a maximum allowed Cr concentration (NSA, 2018). To ensure that the Cr content in slag is below this limit, Cr is kept in molten steel during steel production (this can be controlled by oxygen partial pressure during refining) (Nakajima et al., 2011).

In the samples from China, the median contents of tramp elements were as follows: Cu at 0.08%, Sn at 0.008%, Ni at 0.03%, Cr at 0.08%, and Mo at 0.004%. The impurity levels observed in Chinese samples were lower than in the samples from other countries, with the exception of Sn. The particularly low values found for Cu and Ni can be explained by the limited availability of obsolete products and building materials to be recycled, as well as the high share of primary materials and new scrap input to EAF. Although there are mechanical recycling processes in China (dismantling, shredding, material separation), most ELVs are disassembled manually (Li et al., 2014). The predicted growth in the share of obsolete scrap (McKinsey & Company, 2017) will likely be accompanied by an uptake of mechanical recycling processes, resulting in a higher content of tramp elements. Sn content values are impacted by the number of values under the DL, meaning that the content is overestimated. However, the Sn tolerance limit in the Chinese standard for low-carbon steel plates is higher than in the standards of other countries: this has been attributed to the consumption of locally produced tin-bearing iron ore and ferroalloys (Zhang et al., 2019). It is therefore reasonable to expect the Sn content to be impacted by material input during production.

The Vietnamese samples were produced from a mix of local and imported scrap (specifically, 24% from developed countries). Despite this share of shredded scrap, the samples were found to have low Cu and Sn contents, at 0.09% and 0.007%, respectively. This likely reflects the preliminary treatment of imported scrap: metals like copper and aluminum are handpicked and traded. Local scrap originates from the informal sector: ELVs and WEEE are treated in recycling villages (Kojima, 2018; Salhofer, 2018). Finally, the higher content of Ni and Cr (0.06% and 0.10%) observed in the Vietnamese samples may be attributed to the absence of a market for stainless-steel scrap. This means there is no economic interest for handpicking from imported/collected scrap, and stainless-steel scrap is mixed with other grades.

The values for the samples from Ukraine were between those of the samples from the developed and developing countries. The median contents were as follows: Cu at 0.17%, Sn at 0.009%, Ni at 0.12%, Cr at 0.09%, and Mo at 0.012%. The material separation of ELVs in Ukraine is also conducted mostly manually: parts are dismantled by repair and junk shops for reuse, and partially recycled by the informal sector (Ganoshenko & Holik, 2018).

To compare the obtained results with previously reported tramp elements contents in rebars, the latter must correspond to the defined conditions for studying the accumulation. That is, the representativeness of the variety of grades, charge feed, country-specific accumulation, and number of samples must be consistent. The impurities contents reported for Australia (Miranda et al., 2019) and New Zealand (Lim, 1991) do not correspond to these conditions. In these studies, the samples were collected for a specific steel grade, meaning that the impurity content was kept within the defined limits and is not representative for a variability of rebar grades. Contents for rebars produced from local scrap in Ethiopia (Atsbaha, 2017), Ghana (Kankam, 2004), and Nigeria (Adeleke et al., 2018) have representative patterns of impurities mixing. Even though steel production in these three countries is very limited and relies on the import of steel products (Worldsteel, 2016), the local production of rebars reflects the local scrap supply and recycling system efficiency. While a sufficient number of samples have been investigated for Ethiopia and Ghana, only five samples were used in a study on Nigeria, limiting their representativeness. Thus, the significance of the international comparison was enhanced with the data for Ethiopia and Ghana. These data are illustrated in gray in Figure 2a–e to reflect that these values are not results from our study. In the samples from both of these African countries, the contents of tramp elements are comparable to those of the developed economies. In Ethiopia or Ghana, informal collection and recycling results in manually preprocessed steel fractions in a form of metal and copper–steel–plastic mix (e.g., motors, plugs, hard-switches): this is sold to dealers and steel smelters directly; copper recovery is not carried out (Manhart et al., 2013; Schleicher et al., 2015). Moreover, of the high 215 kt of second-hand EEE Ghana imported mostly from developed countries in 2009, approximately 15% was reported to be nonfunctional (Amoyaw-Osei et al., 2011). These examples indicate that the impurity content of the rebars in these African countries is directly related to the input to the recycling system as well as its efficiency, but does not reflect local consumption.

The review of separation practices during recycling implies that Cu separation in countries where labor-intensive manual disassembly is performed (Vietnam) is more efficient than in countries where mechanical shredding is used. By reviewing the reported tramp elements contents for Ethiopia and Ghana, it was revealed that despite manual disassembly, tramp element accumulation is similar to the developed countries. The difference in the performance of manual dismantling in Vietnam and in these African countries is likely related to the type of goods imported. Vietnam imports different types of scrap from developed countries (heavy and light demolition materials, shredded materials, etc.), followed by metal handpicking, while in Africa, the postconsumer products are imported and treated via informal recycling.

4 | CONCLUSIONS AND FURTHER IMPLICATIONS

Study of the accumulation of impurities in steel is complex because of the multiple variables that impact the phenomena. It is necessary for the methodology and sampling to reflect representative conditions in the country. It is necessary to ensure the samples originate from the same production process, have the same charge composition (here EAF is assumed to avoid primary and new scrap), and have also similar production year. From the results of this study, it can be concluded that the mixing of impurities in steel scrap is not uniform among countries. The content of impurities was shown to be higher in Western Europe and Japan, particularly in the case of Cu and Sn, than in Ukraine, Vietnam, and China. This was shown to be well correlated with the use of mechanical and manual sorting. However, a comparison with African countries shows the variability of handpicking efficiency, and that trade in e-waste increases the pace of local tramp element accumulation. For countries where trade flows do not impact the accumulation, there were several relevant factors besides the recycling technology which were identified: the presence of a market for recovered metals, the quality of material input to secondary steelmaking, steelmaking practices, and the management of byproducts derived from a legislative/economic context.

To fully understand the observed differences of impurity levels between countries, steel alloys and final goods consumption patterns need to be complemented with factors impacting the efficiency of material separation (especially handpicking) and second-hand imports. Additionally, the availability of MFA studies focusing on WEEE and ELVs processing, especially in developing countries, is limited.

Because of the increasing use of steel scrap in the context of climate change mitigation and the transition to a circular economy, it is necessary to consider not only the quantity of recovered materials through high recycling rates, but also the quality of secondary materials. From a material engineering perspective, the composition of scrap does not directly contribute to the quality of secondary materials because properties are determined by microstructure, through processing–structure–property-performance relationships (Olson, 1997). This concept is extended by recovery to integrate the influence of unavoidable impurities and their content on microstructure and desired properties (Daigo et al., 2020). The quality of secondary materials is emerging as a topic of worldwide concern. This is reflected by recent initiatives that aim to avoid the importation of resources of a quality insufficient for recycling. These include the establishment of a market for secondary raw materials for the implementation of a circular economy in the European Union, the Chinese standard for steel scrap import (GB/T39733-2020), and similar legislation proposed in Malaysia (Taylor, 2021). Because steel has a high tolerance to impurity content, the quality of scrap for steelmaking is expressed in terms of physical properties (like scrap origin and size). The desired chemical composition of scrap grades is provided in the European scrap specification (EFR, 2007) and Swedish compilation of requirements for steel and scrap industries, *Skrotboken*. Information on the chemical content of scrap could be the next step in collaboration between the recycling industry and steelmaking. By introducing quality monitoring, recycling facilities could provide information on the quality of scrap, ensure a standardized quality grade, or even comply with specific steelmaking demands. For steelmakers, knowledge of the chemical composition of scrap has the potential to contribute to a higher share of secondary input. This applies especially in the production of flat-rolled products produced by the BOF where constraints regarding the Cu and Sn contents are enforced.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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