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Alloy Profusion, Spice Metals, and Resource Loss by Design

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Abstract: One of the most unfortunate attributes of technology's routine and widespread use of most of the elements in the periodic table is the abysmal functional recycling rates that result from the complexity of modern technology and the rudimentary technological state of the recycling industry. In this work, we demonstrate that the vast profusion of alloys, and the complexities and miniaturization of modern electronics, render functional recycling almost impossible. This situation is particularly true of "spice metals": metals employed at very low concentrations to realize modest performance improvements in advanced alloys or complex electronics such as smartphones or laptops. Here, we present a formal definition of spice metals and explore the significant challenges that product design decisions impose on the recycling industry. We thereby identify nine spice metals: scandium (Sc), vanadium (V), gallium (Ga), arsenic (As), niobium (Nb), antimony (Sb), tellurium (Te), erbium (Er), and hafnium (Hf). These metals are considered fundamental for the properties they provide, yet they are rarely recycled. Their routine use poses severe problems for the implementation of closed material loops and the circular economy. Based on the data and discussions in this paper, we recommend that spice metals be employed only where their use will result in a highly significant improvement, and that product designers place a strong emphasis on enabling the functional recycling of these metals after their first use.

Keywords: metal alloys; spice metal; electronic materials; functional recycling; product design

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1. Introduction

In today's technology, the vast profusion of alloys, and the complexities and miniaturization of modern electronics, render functional recycling almost impossible. Nonetheless, the mining and materials processing industries commonly promote metals as materials that can be reused indefinitely. This position would hold true, in principle, if recovery processes and separation technologies were 100% efficient. In practice, the quality of recycled materials progressively deteriorates [1,2]. This progressive degradation happens for practically all materials, including paper [3], plastics [4,5], and metals [6–9]. The decline in material quality stems from both technical challenges and practical issues. From a technical standpoint, material separation is complex, costly, and associated with non-trivial environmental impacts [10,11]. From a practical standpoint, current practices in collecting recyclable materials result in heavily mixed and contaminated waste streams [12,13]. What this means is that many materials are technically recyclable, but their dispersion and inclusion in mixed material products, chiefly alloys, render recycling economically unfeasible, if not downright impossible.

At a time when the yearly demand for major metals is soaring to historic highs [14,15], product designers rarely consider enabling reuse to be part of their remit [16]. Collection, sorting, and recycling practices often do little more than separate metal flows into steel, aluminum, and copper alloy groups. Raabe et al. make the telling comment that [17], "Current structural alloys are not devised for end-of-life but rather for one-time use." The situation is particularly impactful regarding elements used in small amounts to modestly improve the performance of alloys. Similarly, many elements are employed in small quantities in several modern electronic components [18–20]. In both cases, these elements, which are often necessary to obtain set design performances, are rarely capable of being recovered and reused. They can be regarded as "lost by design" [21].

In this paper, the challenges to modern technological approaches are addressed from three interrelated perspectives: the routine use of large numbers of difficult-to-distinguish alloys (Section 2), the use of small quantities of scarce metals ("spice metals") that are often difficult to identify and separate (Section 3), and the absence of a technologically sophisticated and fully informed end-of-use recycling sector (Section 4). In the final section (Section 5), we advocate several approaches with strong potential for more insightful material choice and eventual reuse at the end of the material's initial employment.

2. Alloy Profusion

Until the late 20th century, the whole manufacturing sector was served by a modest number of alloys—mixtures of a "host" metal with minor-to-moderate amounts of alloying metals. For example, the composition of 4140 steel, one alloy ordinarily used in the automotive industry, is Fe (balance); 0.80–1.10 Cr; 0.15–0.25 Mo; 0.38–0.43 C; 0.75–1.00 Mn; <0.035 P; <0.040 S; 0.15–0.35 Si [22], and that for the beryllium copper alloy C17200 is Cu (balance); 1.80–2.00 Be; >0.20 Ni + Co; <0.60 Ni + Co + Fe [23] (all figures are expressed in weight %). Materials designers, however, increasingly cater to those seeking new materials by emphasizing specific properties for specific uses, and those properties often require additional complexity in alloy formulation. There are good business reasons to embrace alloy complexity and specificity. The alloy supplier can charge a premium for a bespoke material, while the manufacturer can create a (perhaps marginally) better-performing product. Over time, these incentives have resulted in the creation and use of vast numbers of different alloys: there are currently more than 3500 iron alloys [24,25], more than 1800 copper alloys [26], and several hundred aluminum alloys [27], to name the most alloy-abundant of the host metals. Many of these alloys incorporate (at low concentrations) one or more of the "spice metals" (refer to §3 for details). For example, the aluminum alloy 6060 is typically Al (balance), 0.4 Mg, 0.4 Si, and 0.2 Fe, plus even smaller amounts of Cu, Mn, Cr, Zn, and Ti [28] (all numbers expressed as wt%).

In a recent further expansion of alloy profusion, high-entropy alloys (HEAs) have emerged and are being widely explored [29–31]. Typically incorporating five or more elements such as the 3d transition metals Cr, Mn, Fe, Co, and Ni, HEAs provide yield strength and fracture toughness that exceed those of other alloys. For that reason, HEAs are being considered for various industrial uses. Even though these specialized alloys promise exciting and valuable applications, they exacerbate an already existing problem from a long-term sustainability perspective: they are almost certain to be usefully employed only once. This situation occurs because, to be reused, alloys would need to be positively identified when discarded along with an unpredictable mixture of the 5000+ alloys now in service. It is also of interest that, except for iron, all of the elements in the most commonly explored HEAs have been designated as critical by several government agencies [32–38]. Thus, once the alloys are used and discarded, they should be identified, recovered, and the alloys or elements therein reused.

3. Spice Metals

Spices are often thought of as aromatic substances of vegetable origin used for flavoring foods [39]. However, a definition that is more useful and expansive for the present discussion is: "that which enriches or alters the quality of a thing in a small degree, as spice alters the taste of food." (An example of the latter usage is "the spice of life.") From this perspective, about a decade ago, the term "spice metal" began sporadically appearing in the literature (first, it seems, by Reller et al. [40], followed by Senk et al. [41] in 2012), in book chapters (e.g., Hieronymi (2012) [42]), and in conference presentations (e.g., Hagelüken (2013) [43]). Spice metals, in spite of their modest concentrations, provide significantly improved material properties to the materials of which they are a minor but essential part.

Senk and colleagues identified nine elements plus the platinum group metals (PGMs) as spice metals on the basis of their importance for seven mobility systems [41]. (The PGMs were, presumably, platinum, palladium, and rhodium, which are used for emission control [44,45].) However, the researchers did not explore the topic further—they offered no guidance on how the elements were selected, nor did they relate the topic to any other industrial uses. A year later, Hagelüken selected forty-five different elements as spice metals, again without providing any guidance on the selection process [43]. It is unclear whether nine elements are too few to call out for this distinction, but forty-five seems to be so many as to make the distinction almost meaningless. Given the past murky approaches to spice metal categorizations, there appears to be a need for a precise and transparent definition.

A Formal Definition for Spice Metals

What might be the definition of a spice metal? We classify a metal as "spice metal" when it is employed at concentrations less than or equal to 1 wt% in alloys in applications that together employ more than 5 wt% of the total use of the metal, and with an end-of-use functional recycling rate (EoU-FRR) < 20% (Equation (1)). By functional recycling rate, we mean recycling that reuses the element so as to take advantage of its particular attributes, rather than being recycled with other elements into a material in which such attributes are lost, as in the case of steel reinforcing bars. The requirement for functional recycling is justified because most elements are downcycled.

$$\begin{aligned} &Spice\ metal\ in\ alloys \\ &= \begin{cases} Concentration\ in\ an\ alloy\ application\ X\ \leq 1\ \text{wt\%} \\ Total\ metal\ use\ in\ alloy\ application\ X\ \geq 5\ \text{wt\%}\ of\ all\ uses \\ End-of-use\ functional\ recycling\ rate < 20\% \end{cases} \end{aligned} \quad (1)$$

Given this definition, we then searched the scientific literature and relevant databases for the compositions of specific alloys or alloy families that contain spice metals at low concentrations, in agreement with the limits specified (see Table 1 for references). Examples include niobium in steel alloys [46], hafnium in superalloys [47], and vanadium for high-strength low-alloy steels [48]. All these metals are used at <1 wt% concentration in one application whose total use as an alloy is >5 wt% of the total use of the element, and whose end-of-use functional recycling rate does not reach 20%. We arrived at a list of nine metals: scandium, vanadium, gallium, arsenic, niobium, antimony, tellurium, erbium, and hafnium (Figure 1).

Table 1. Categorization of relevant elements as spice metals. The symbol ✓ confirms the eligibility for spice metal criteria, while ✘ indicates that the metal does not meet the required characteristics. When a metal has a ✓ in all the columns, we consider it a spice metal.

Element			Total Alloy Use in at Least One Application ≥ 5% [a]	End-of-Use Functional Recycling Rate < 20% [a,b]	Concentration ≤ 1% in One Application Whose Total Alloy Use ≥ 5% [c]
2	He	Helium	✘	✓ (3%)	✘
3	Li	Lithium	✘	✓ (3%)	✘
4	Be	Beryllium	✓ Industrial components, aerospace, automotive, electronics, telecommunications	✘ (21%)	✘
5	B	Boron	✘	✓ (4%)	✘
6	C	Carbon (graphite)	✘	✓ (10%)	✘
9	F	Fluorine	✓ Aluminum fluoride	✓ (0%)	✘
12	Mg	Magnesium (metal)	✓ Die-castings, aluminum alloys, nodular cast iron	✘ (39%)	✘

Table 1. *Cont.*

Element			Total Alloy Use in at Least One Application ≥ 5% [a]	End-of-Use Functional Recycling Rate < 20% [a,b]	Concentration ≤ 1% in One Application Whose Total Alloy Use ≥ 5% [c]
13	Al	Aluminum	✓Transportation, packaging, construction, electrical, consumer durables, machinery	✘ (60%)	✘
14	Si	Silicon (metal)	✓Aluminum alloys, solar applications, electronics	✘ (63%)	✘
15	P	Phosphorus	✘	✓(0%)	✘
19	K	Potassium	✘	✓(0%)	✘
21	Sc	Scandium	✓Aerospace, sporting goods	✓(5%)	✓Al alloys (0.3%) [d]
22	Ti	Titanium (metal)	✓Aerospace, other alloys	✘ (70%)	✘
23	V	Vanadium	✓High-strength low-alloy steel, special steel	✓(5%)	✓TRIP steel (<0.1%) [e]
24	Cr	Chromium	✓Stainless steel	✘ (36%)	✘
25	Mn	Manganese	✓Steel alloys, non-steel alloys	✘ (53%)	✘
26	Fe	Iron	✓Steel alloys	✘ (78%)	✘
27	Co	Cobalt	✓Superalloys, cemented carbides, magnets	✘ (68%)	✘
28	Ni	Nickel	✓Stainless steel, alloy steel, Ni-Cu alloys	✘ (60%)	✘
29	Cu	Copper	✓Constructions, transportation, consumer goods	✘ (48%)	✘
30	Zn	Zinc	✓Zinc alloys	✘ (52%)	✘
31	Ga	Gallium	✓Integrated circuits	✓(5%)	✓Electronics (0.001%) [f]
32	Ge	Germanium	✓Eletrical, solders	✘ (30%)	✘
33	As	Arsenic	✓Semiconductors, copper alloys	✓(1%)	✓Arsenical Copper Alloys (<0.5%) [g]
34	Se	Selenium	✓Semiconductors	✓(5%)	✘
37	Rb	Rubidium	✘	✓(0%)	✘
38	Sr	Strontium	✘	✓(1%)	✘
39	Y	Yttrium	✘	✓(1%)	✘
40	Zr	Zirconium	✘	✓(1%)	✘
41	Nb	Niobium	✓Steel alloys, superalloys	✓(6%)	✓TRIP steel (0.04%) [e]
42	Mo	Molybdenum	✓Steel alloys, stainless steels, tool steels	✘ (30%)	✘
44	Ru	Ruthenium	✓Electrical components	✓(10%)	✘
45	Rh	Rhodium	✘	✘ (60%)	✘
46	Pd	Palladium	✘	✘ (60%)	✘
47	Ag	Silver	✓Automotive, industrial machinery, electronics	✘ (35%)	✘
48	Cd	Cadmium	✓Alloys	✘ (23%)	✘
49	In	Indium	✓Alloys, solders	✓(5%)	✘
50	Sn	Tin	✓Solder, tinplate, lead-acid batteries	✘ (30%)	✘
51	Sb	Antimony	✓Lead alloys	✓(5%)	✓Lead alloys (1%) [h]
52	Te	Tellurium	✓Solar power, thermo-electric, metallurgy	✓(1%)	✓Steel and lead alloys (<1%) [i,j]
55	Cs	Cesium	✘	✘ (67%)	✘
56	Ba	Barium	✘	✓(0%)	✘
57	La	Lanthanum	✓Batteries, metal alloys	✓(0%)	✘
58	Ce	Cerium	✓Metal alloys, batteries	✓(0%)	✘
59	Pr	Praseodymium	✓Magnets, metal alloys, batteries	✓(1%)	✘
60	Nd	Neodymium	✓Magnets, metal alloys, batteries	✓(1%)	✘
62	Sm	Samarium	✓Batteries	✓(1%)	✘

Table 1. *Cont.*

Element			Total Alloy Use in at Least One Application ≥ 5% [a]	End-of-Use Functional Recycling Rate < 20% [a,b]	Concentration ≤ 1% in One Application Whose Total Alloy Use ≥ 5% [c]
63	Eu	Europium	✘	✓(0%)	✘
64	Gd	Gadolinium	✘	✓(1%)	✘
65	Tb	Terbium	✓Magnets	✓(1%)	✘
66	Dy	Dysprosium	✓Magnets	✓(0%)	✘
67	Ho	Holmium	✘	✓(1%)	✘
68	Er	Erbium	✓Vanadium alloys	✓(3%)	✓Vanadium alloys (< 0.6%) [k]
69	Tm	Thulium	✘	✓(1%)	✘
70	Yb	Ytterbium	✘	✓(0%)	✘
71	Lu	Lutetium	✘	✓(0%)	✘
72	Hf	Hafnium	✓Superalloys, machinery	✓(1%)	✓Superalloys (0.15%) [l]
73	Ta	Tantalum	✓Superalloys, mill products, carbides	✘ (20%)	✘
74	W	Tungsten	✓Cemented carbides, steels, mill products	✘ (25%)	✘
75	Re	Rhenium	✓Superalloys	✘ (52%)	✘
76	Os	Osmium	✘	✓(0%)	✘
77	Ir	Iridium	✓Electrical	✘ (25%)	✘
78	Pt	Platinum	✘	✘ (65%)	✘
79	Au	Gold	✓Jewelry	✘ (90%)	✘
80	Hg	Mercury	✓Dental amalgams, electronics	✘ (44%)	✘
81	Tl	Thallium	✘	✓(0%)	✘
82	Pb	Lead	✘	✘ (92%)	✘
83	Bi	Bismuth	✓Fusible alloys, metallurgical additives	✓(1%)	✘
92	U	Uranium	✘	✓(0%)	✘

Notes.[a] Graedel et al., (2022) [47]. [b] UNEP (2013) [48]. [c] The concentration in alloys was investigated only for those elements that showed eligibility for the spice metal label in the first two categories (i.e., alloy use ≥ 5 wt% and end-of-use functional recycling rate < 20%). [d] AZO Materials (2022) [49]. [e] Oja et al., (1998) [46]. [f] Korf et al., (2019) [19]. [g] Carapella (2002) [50]. [h] Prengaman (2009) [51]. [i] Yaguchi and Onodera (1988) [52]. [j] Guo et al., (2009) [53]. [k] Wu et al., (2019) [54]. [l] Pollock and Tin (2006) [55].

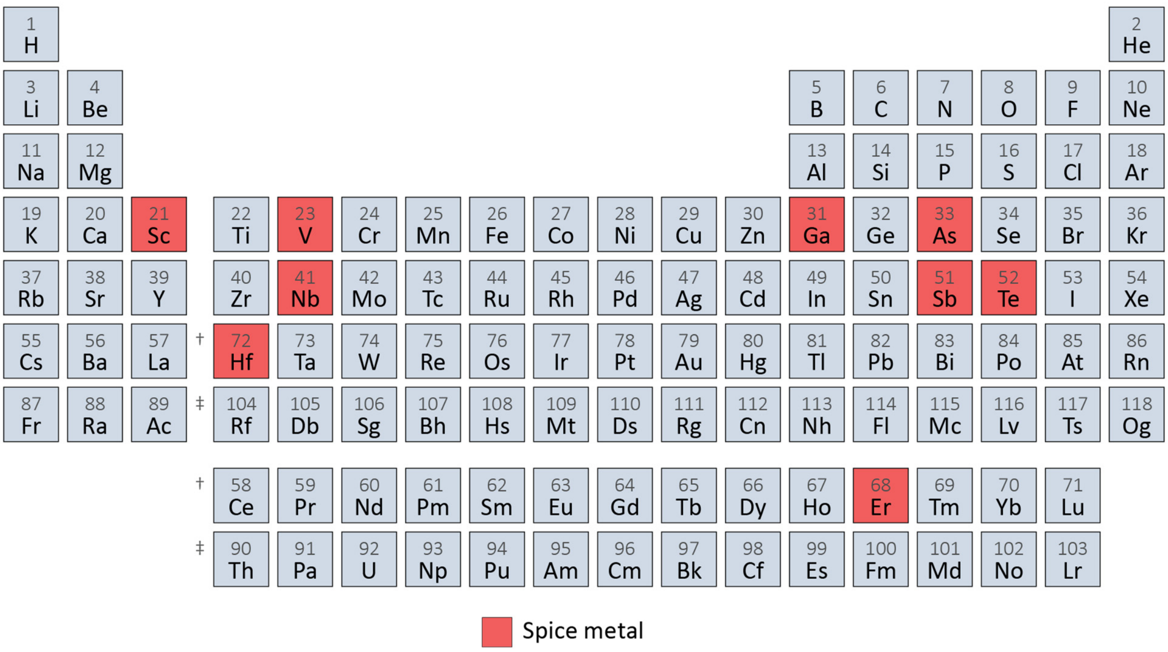

Figure 1. Periodic table of elements with the spice metals highlighted.

It is possible to check the nine-metal list for veracity by investigating some of the challenging properties one would expect to find, which is carried out in Table 2. All elements, except for vanadium, display low crustal abundance. Similarly, all of these elements are considered critical by one or more governmental agencies.

Table 2. Challenging properties of spice metals.

Atomic Number	**21**	**23**	**31**	**33**	**41**	**51**	**52**	**68**	**72**
Chemical Symbol	**Sc**	**V**	**Ga**	**As**	**Nb**	**Sb**	**Te**	**Er**	**Hf**
Upper crustal abundance [ppm] [a]	14	106	18.6	5.7	11.6	0.75	0.03	2.30	5.07
Toxicity concerns [b]		✓		✓		✓			
Significant use in information technology [c]				✓		✓	✓		✓
Critical element in Australia [d]	✓	✓	✓		✓	✓		✓	✓
Critical element in Canada [e]	✓	✓	✓		✓	✓	✓	✓	✓
Critical element in the European Union [f]	✓	✓	✓		✓	✓		✓	✓
Critical element in Japan [g]		✓	✓		✓	✓	✓	✓	✓
Critical element in the United States [h]	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: [a] Hu and Gao (2008) [56]. [b] Pourret and Hursthouse (2019) [57]. [c] Ku (2018) [58]. [d] Australian Government (2020) [34]. [e] Government of Canada (2021) [35]. [f] European Commission (2017) [32]. [g] Ministry of Economy, Trade, and Industry (METI) of Japan (2022) [38] and Nakano (2021) [36]. [h] U.S. Department of the Interior (2018) [33].

Rhenium is one important metal that did not make the list of spice elements but is worth mentioning. Rhenium's end-of-life recycling rate is high, and thus would tend to suggest that its supply is not at risk. However, rhenium's primary use is in aircraft engine superalloys, which are numbered and recovered so as not to lose the metal, which is of a very high value. In this situation, the high recycling rate stems from the very high monetary value of the superalloy, as well as its spice metal characteristics.

4. Serviceable Resources: Abandonment or Reuse?

When alloys were few, their identification was relatively straightforward. Disassembly of easily recoverable valuable components, such as catalytic converters, color sorting (e.g., for copper and its alloys), and eddy current separation (e.g., for aluminum materials), enabled reasonable second uses of the base metals in many alloys. As metallurgy became more sophisticated over time and industrial materials became more element-diverse, separation grew increasingly difficult [59–61]. This situation is of particular concern for the spice metals, the bulk of whose uses are in alloy form or other complex assemblages, as well as in the low concentrations typical of modern alloys such as HSLA steels, alloy steels, personal computers, and the like.

An additional complicating factor for element reuse concerns products that are designed to be dissipated during use (e.g., brake linings, fireworks, hardfacing treatments) so that recovery for reuse is not an option [62,63]. Another problem arises for uses for which no technology has been developed to permit element-targeted recycling, such as polishing compounds, ceramics, and glass additives. To study these challenges further, Ciacci et al. [21] evaluated the recycling potential of sixty metals, assigning their major uses into four categories: potentially functionally recyclable, currently unrecyclable, in-use dissipated, and unspecified. For the spice metals listed in Figure 1, the results of Ciacci et al. are given in Table 3. We compare that information with estimates of end-of-use recycling in the rightmost column [47,64]. It is evident that the actual recycling that occurs for most of these elements is far less than the potential recycling suggested by the analysis of Ciacci et al.

Table 3. Recycling potentials and realizations for the major uses of eleven spice metals (% of total uses).

	Element		Potentially Recyclable [a]	Presently Unrecyclable [a]	Dissipated During Use [a]	Unspecified [a]	Current Recycling [b]
21	Sc	Scandium	90%	0%	0%	10%	5%
23	V	Vanadium	97%	1%	0%	2%	5%
31	Ga	Gallium	18%	76%	0%	6%	5%
33	As	Arsenic	14%	64%	17%	5%	1%
41	Nb	Niobium	92%	0%	0%	8%	6%
51	Sb	Antimony	26%	66%	4%	4%	5%
52	Te	Tellurium	85%	10%	5%	0%	1%
68	Er	Erbium	0%	100%	0%	0%	3%
72	Hf	Hafnium	81%	13%	0%	6%	1%

Notes: [a] Ciacci et al., (2015) [21]. [b] Graedel et al., (2022) [47] and UNEP (2013) [64].

Our point regarding recycling challenges is expressed visually in Figure 2. The abscissa variable is the compositional percent of an element in its dominant use, and is plotted with zero at the right (i.e., the further an element is plotted to the right, the lower its concentration). The ordinate variable is the end-of-use functional recycling rate, with origin at the top (i.e., the higher an element is plotted, the less efficiently it is recycled). As mentioned earlier, the functional recycling rate refers to reuse that retains the element's properties, rather than reuse resulting from merging the discards with other metals and alloys, and thus nullifying the element's functional properties. To provide perspective, we plot all of the spice metals from Figure 1, plus a few of the commonly used major elements. The actual data and references are available in Table S1 of the Supplementary Information.

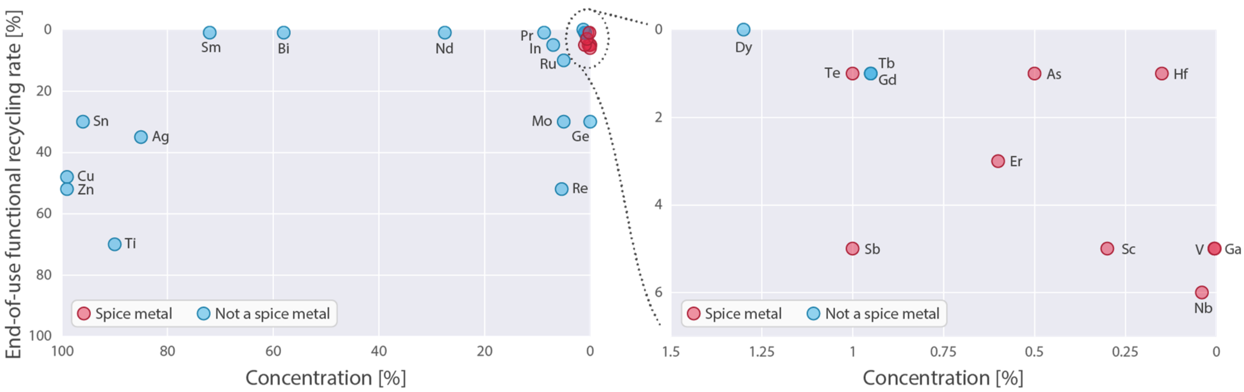

Figure 2. Losses to non-functional recycling as a function of the concentration (%) of the spice metals in their dominant uses.

The central message of Figure 2 is evident at a glance: the spice metals are nearly all clustered in the 0,0 (upper right) corner, i.e., minimal (but essential) in-use concentrations and minimal or negligible functional recycling. On the diagram, the electronics metals are more widely dispersed: several have end-of-use functional recycling rate levels above 50% (but mostly still well below 100%). Clearly, the spice metals that enable much of modern technology (especially the alloy steels and high-strength low-alloy (HSLA) steels) see only a single use, after which their unique benefits are lost to technology forever. Given the rapid increase in the use rates of several spice metals (e.g., Henckens (2022) [65]), these abysmal recycling statistics are a significant cause of concern.

5. Discussion and Conclusions

As the above summaries demonstrate, the complexity of materials in today's highly engineered products is rapidly increasing. Examples of this trend are easy to find, from the sixty or more elements contained in modern electronics [66] to the stunning seventy-six elements utilized in modern automobiles [67]. In each case, many of these elements are used in minimal amounts, so that identifying, separating, and then using them again imposes significant analytical, technical, economic, and managerial loads on the recycler.

The situation presented in Table 3 arises in large part because materials scientists and product designers rarely consider material reuse [68]. For example, in extensive reviews of progress in computational materials design [69] and in novel materials for clean energy [70], the need for material reuse is never mentioned, even though it is obvious that supplies of the full range of periodic table elements cannot be regarded as perpetual. Indeed, the mere existence of criticality lists indicates the need to carefully (re)consider the degree to which modern society employs and reuses materials, both in quantity and diversity.

It is encouraging that some in the materials science community are beginning to recognize this situation and consider how it might be changed. Barnett et al., (2020) [71] propose that, in some instances, such as a group of nickel-containing alloys in combination with 316 stainless steel, mixtures of these alloys can generate a suitable alloy product, perhaps with some adjustments in the melt composition. Nonetheless, the authors view this approach as practical only for the higher-value and lower-tonnage flows, and alloy identification at the end of product use is still likely to present a significant challenge.

In a comprehensive review relating sustainability to alloy design, Cann et al., (2021) [72] discuss several alloy groups and their recycling challenges. The authors' major point is that the trend toward employing increasingly complex alloys with the goal of performance enhancement results in heightened complexity at the recycling stage. Furthermore, from a climate sustainability perspective, the central roles of the widely used iron and aluminum alloys may benefit more from service life enhancement than from increased recycling and reuse rates.

Raabe et al., (2019) [17] also propose that this situation could be significantly improved by employing a limited compositional spectrum of materials. Unlike the proposals of Barnett et al. [71] and Cann et al. [72], Raabe and colleagues [17] realize that a focus on widely-used iron and aluminum alloy families has the most significant potential to influence climate change (a complementary goal to improving end-of-life recycling) by reducing emissions among the most prolific energy users.

An alternative approach to current alloy employment is that of Li and Lu (2019) [73], who advocate the "plainification" of alloys: the design of tailored and stabilized interfaces at grain boundaries, in lieu of achieving improved performance by adding additional alloying elements. Experiments employing a unified steel concept in car manufacturing appear to support the "plainification approach" [74]. A promising example of material reuse thinking from a designer's perspective is that of the Ford Motor Company with respect to its all-aluminum F-150 truck [75]. The vehicle chemistry involves several alloy families and nine different elements: Mg, Al, Si, Ti, Cr, Mn, Ni, Cu, and Zn. While none of the nine is a spice metal by our definition, Ford's approach offers a valuable perspective for spice metal users. Ford recognized that using a small number of materially compatible alloys enabled process scrap to be merged and returned to the alloy suppliers for remelting, thus saving money, minimizing energy use in the production of new alloys, and generating an environmental benefit. The environmental benefits extend to the product at end-of-use, when recycling and reuse are better enabled. One might describe this design approach as optimizing the functional reuse potential (sometimes indicated as FRP) of the product.

Thus, some detailed thinking about specific alloys and their recycling potential is now beginning, but there are few solid plans for improving the general situation. Perhaps a place to start is to focus on the metals in Table 1, and try to avoid their inclusion in the development of new alloys. Nevertheless, this is easier said than done, especially when the inclusion of spice metals is tied to marginal performance gains required to keep a product ahead of—if not at the very least in line with—the competition. A potentially more rewarding approach could be for alloy and electronics designers and company CEOs to visit the recycling centers that would have to deal in the future with what might emerge from today's material design communities. The designers will find that the vast number of alloys and the meager concentrations of many alloying elements make sorting and recovering metals for reuse at the end of service life to be essentially impossible, or, at the very least, extremely complex. Material design might actually become more sustainable if those who design new materials must consider the paths to multiple stages of use for each element as part of the design process. This argument is being actively explored in the extended producer responsibility discourse [76].

It may occur to readers that some of the spice metals have from time to time been labeled "heavy metals" as a consequence of their possible health effects (e.g., Aposhian (1983) [77], Ordog (2006) [78], Aijaz et al., (2022) [79]). The use of the term "heavy metals" has, however, long been shown to be arbitrary and imprecise [80]. A committee of the International Union of Pure and Applied Chemistry emphasizes that "we should abandon classification of metals using terms such as 'heavy metals' which have no sound terminological or scientific basis" [81]. Unlike the term "heavy metals," spice metals in alloys and electronics have been clearly defined in the present work, both with the intent to bring heightened visibility to the value of small amounts of these metals in modern technology, and to encourage their systematic reuse.

In conclusion, product inventors, designers, and fabricators must become increasingly serious about how they use and/or reuse materials. If they do not, the materials will be "lost by design," as the title of this paper implies. If they do take these problems seriously, decades from now, their reward for doing so will be to have helped enable a world that is, from a materials perspective, much more sustainable.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137535/s1, Table S1 reports the information employed in constructing Figure 2 of the main manuscript. References [82–94] are cited in the supplementary materials.

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