DOI: 10.1111/jiec.13289

FORUM

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

A terminology for downcycling

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Editor Managing Review: Reid Lifset

Funding information
German Environment Agency (UBA), grant no. FKZ 3717313490.

Abstract

The term downcycling is often used anecdotally to describe imperfections in recycling. However, it is rarely defined. Here, we identify six meanings of the term downcycling as used in scientific articles and reports. These encompass the material quality of reprocessed materials, target applications, product value, alloying element losses, material systems, and additional primary production. In a proposal for harmonized and more specific terminology, we define downcycling as the phenomenon of quality reduction of materials reprocessed from waste relative to their original quality. We further identify that the reduced quality can express itself thermodynamically, functionally, and economically, covering all perspectives on downcycling. Dilution, contamination, reduced demand for recycled materials, and design-related issues can cause those downcycling effects. We anticipate that this more precise terminology can help quantify downcycling, keep materials in the loop longer, use materials more often and at higher quality, and therefore assist in reducing material-related environmental impacts.

KEYWORDS
circular economy, downcycling, downgrading, industrial ecology, recycling, waste

1 | INTRODUCTION

Basic materials production causes at least 13% of global direct and indirect greenhouse gas emissions, particularly metals, chemicals, and cement (Lamb et al., 2021). Improving resource and material efficiency in key sectors would reduce the environmental impacts caused by material production, representing an important step to climate neutrality (Pauliuk et al., 2021). In particular, shifting material production from primary to secondary production would reduce linked emissions because secondary production generally causes lower emissions than primary production, as exemplified for metals by Van der Voet et al. (2019), for plastics by Zheng and Suh (2019), and for glass by Larsen et al. (2009). Furthermore, higher circularity is seen as a means to address raw material criticality (Espinoza et al., 2020). However, even many metals, theoretically extensively recycled, dissipate quickly into receiving mediums from which recovery is technically or economically unfeasible (Helbig et al., 2020). Short lifespans and imperfect recycling are also issues in the plastics sector (Wang et al., 2021). The European Commission adopted a new Circular Economy Action Plan as part of its European Green Deal agenda to promote circular economy processes and keep resources in the economy (European Commission, 2020).

The core of this circular economy includes the “3Rs” (reduce, re-use, recycle). However, neither is the concept of circular economy finalized (Kirchherr et al., 2017) nor is the list of so-called R-imperatives conclusive (Reike et al., 2018). In the context of recycling, circular economy, or material and product cycles in general, sometimes the term "downcycling" or "downcycled" appears (Di Maria et al., 2018; Glogic et al., 2021; Ihnát et al., 2020; Koffler & Florin, 2013; Ortego et al., 2018a; Zhang et al., 2020). The term "downgrading" or "downgraded" is used similarly (Bakker et al., 2019; Worrell et al., 2016). Very broadly, the term downcycling is used to describe aspects of imperfections in the material and product cycles beyond thermodynamically unavoidable losses. For example, Geyer et al. (2016b, 1011) take a critical and nuanced position to various forms of material recycling and write that "downcycling is considered a less desired form of recycling." Many other authors share this view but very often do not specify their definition of downcycling. Therefore, whether a specific case should be considered downcycling often remains unclear. The conclusion then depends on the specific perspective taken. Table S1 in the Supporting Information lists quotes from the references and the classification of each quote. We do not intend to define the term "upcycling" here, which can be seen as the antonym of downcycling because that is a matter of its own. In brief, upcycling is discussed and already reviewed, for example, as a creative practice (Bridgens et al., 2018), in the textiles industry (Paras & Curteza, 2018), and for chemicals and plastics (Korley et al., 2021). Upcycling is not an issue when focusing on closing material cycles, but downcycling is an existing and complex problem. Therefore, we focus on the terminology for downcycling.

This article first shows that substantially different interpretations of the downcycling phenomenon exist. We collect a large variety of perspectives without judging their suitability or appropriateness. We argue that these different interpretations exist because downcycling has never been adequately defined. If the term is not well defined, it can hardly be satisfactorily measured. If downcycling cannot be measured, it cannot be managed, let alone be avoided—given that is what is environmentally or economically beneficial. Such definitions are also part of a work program of the Joint Working Group on Secondary Materials of ISO Technical Committees on Life Cycle Assessment and Circular Economy (ISO, 2022). Therefore, we develop a general concept of downcycling, covering various researchers' articles and reports. We further develop a terminology for downcycling to overcome the ambiguity in using the downcycling term. This terminology enables corporate and regulatory actions to identify, quantify, and limit downcycling phenomena with the overarching goal of reducing material-related environmental impacts. The concept is generally applicable to all recyclable materials like metals, minerals, plastics, natural fibers, or pulp and paper. However, we focus on metal and mineral resources and exemplify the concept with the case of aluminum recycling.

2 | DEVELOPMENT OF A DOWNCYCLING CONCEPT

The term "downcycling" is a neologism to describe downward recycling. Downward in this context means that it is unintended or even undesired from a material systems perspective or society at large. Downcycling may, however, be profitable for individual actors like recyclers due to specific market conditions. Nevertheless, a generally accepted definition for downcycling has not been published. It is ambiguous what the term includes and what it measures. In contrast, "recycling" is defined and found in legal documents like the European Union's Waste Framework Directive.

> **Recycling**: "Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations." (Directive, 2008/98/EC)

We acknowledge that this recycling definition still leaves room for interpretation and various indicators to measure successful recycling (Haupt et al., 2017). However, it is not the purpose of this article to delve into a recycling discussion. Here, we focus on downcycling terminology.

For the term downcycling, such a universally accepted definition does not exist. Therefore, a general concept for the term downcycling is deduced in this section by literature analysis. We further below specify and exemplify this concept for the case of metals recycling. Authors often use downcycling almost casually or anecdotally in just a few sentences of their articles or reports. There are, of course, a few exceptions. Di Maria et al. (2018) and Zhang et al. (2020) compare downcycling and recycling construction and demolition waste. Glogic et al. (2021) analyze environmental tradeoffs from downcycling in the case of alkaline batteries, while Ihnát et al. (2020) assess the downcycling of wood and Koffler and Florin (2013) look at value-corrected substitution in life cycle assessment and its relation to downcycling. Finally, Ortego et al. (2018a) thermodynamically quantify downcycling in automobile recycling. However, these authors do not provide a detailed definition of downcycling before starting their assessments.

Geyer et al. (2016b) argue that recycling material multiple times is not necessarily better than recycling only once, and performing closed-loop recycling is not necessarily better than open-loop recycling. It all comes down to the environmental impacts and damages to areas of protection associated with primary and secondary production and the impacts of fabrication and manufacturing, which are quantified with the method life cycle assessment. Geyer et al.'s (2016b) distinction between closed-loop recycling and open-loop recycling is usually clear because either the material is used for the same function again or not. The distinction is also nonjudgmental because whether a loop is open or closed is, linguistically, neither good nor bad.

They further explain that "recycling is sometimes called *downcycling* when the recycled material is of lower quality and functionality than the original material" (Geyer et al., 2016b, 1011). They add that "downcycling manifests as changes in the inherent properties of the recycled material" (Geyer et al., 2016b, 1011), following the definition of open-loop recycling in ISO 14044 (ISO, 2021). The quotes from Geyer et al. (2016b)—picked as a representative example and many similar quotes can be found in the literature—exemplify the fundamental problems occurring whenever

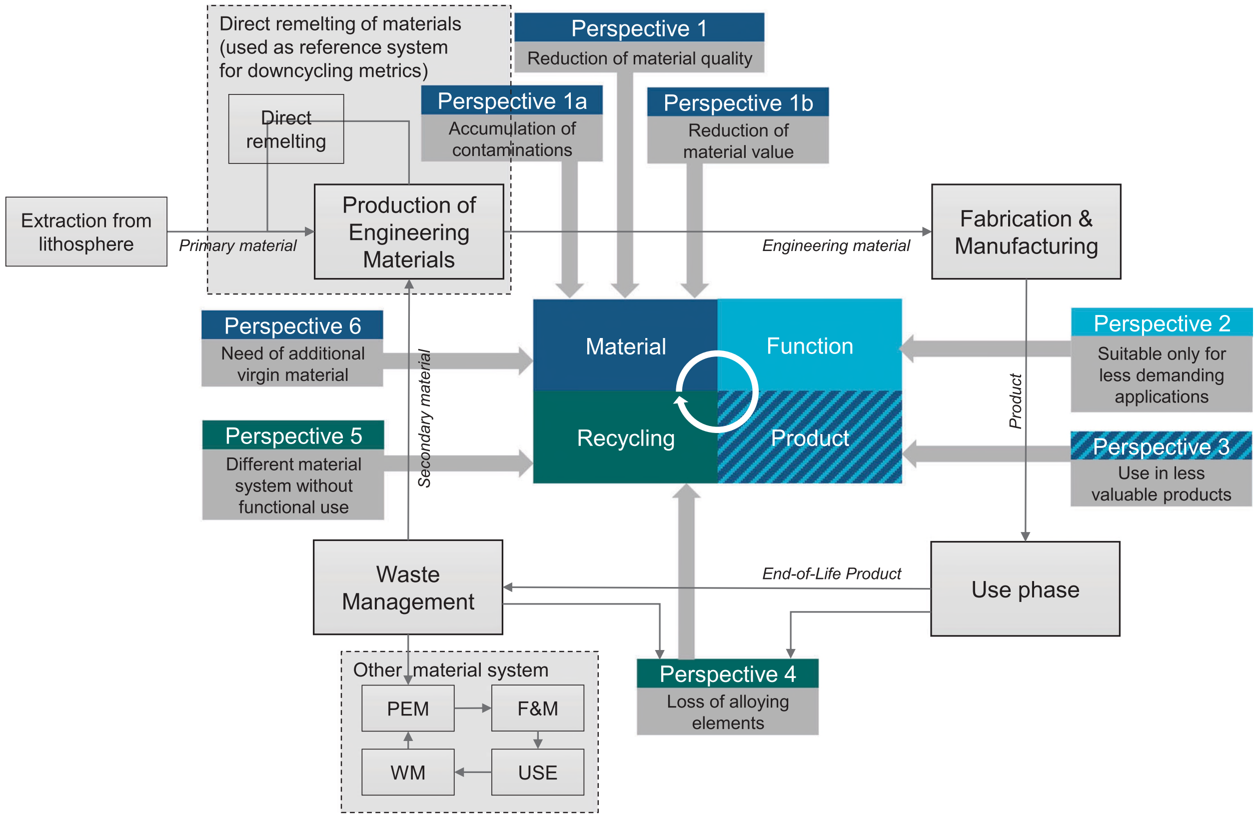

FIGURE 1 Scheme of processes for material production, use, and reprocessing and the connecting material flows, including six perspectives on the downcycling phenomenon extracted from more than 50 quotes in scientific articles and reports (see Table S1 in the Supporting Information). PEM: Production of Engineering Materials. F&M: Fabrication & Manufacturing. USE: Use phase. WM: Waste Management

downcycling is described. If downcycling is necessarily less favorable than "true", high-quality, or functional recycling, where do we draw the line between recycling and downcycling? For whom is downcycling bad? How can we quantify aspects like quality, functionality, or inherent properties that Geyer et al. (2016b) mention?

Instead of jumping to a conclusion, it is worthwhile looking at the various perspectives. The more than 50 references listed in the Supporting Information take one or more of six general perspectives on downcycling, with two additional subcases. Figure 1 summarizes the findings of these perspectives and locates them in the material cycle, using the Unified Materials Information System (UMIS) terminology by Myers et al. (2019): Materials are extracted from the lithosphere, enter the production stage of engineering materials (PEM), are then fabricated and manufactured (F&M) into products, which in turn are used in the use phase (USE), after which the materials are recycled in the waste management stage (WM). Some authors mention multiple aspects of downcycling; therefore, they appear multiple times. None of the authors attempted to give a similar overview on downcycling perspectives. To address this, we organize the perspectives into six categories.

2.1 | Reduction of material quality

The first downcycling perspective is that *reprocessed materials are of lower quality than original materials* because of downcycling. This perspective is taken by Bachmann et al. (2018), Bakker et al. (2019), Corona et al. (2019), Geyer et al. (2016a), 2016b, Deckert (2016), European Commission (2013), Gala et al. (2015), Gößling (2001), Haas et al. (2015), Huysman et al. (2015), Horodytska et al. (2020), Koffler and Florin (2013), Kristof and Hennicke (2010), Mohajan (2020), Ortego et al. (2018a), Orzol and Lieberwirth (2018), Risse et al. (2019), Sanchis-Sebastiá et al. (2021), Tanguay et al. (2021), and Worrell et al. (2016).

It is impossible to universally define "material quality" in this general formulation because it depends entirely on the material's function and purpose. It could mean mechanical properties (e.g., strength, elasticity, stiffness, hardness) just as much as other physical properties (e.g., thermal and electrical conductivity, optical density, opacity). It could also mean resistance to oxidation, corrosion, or abrasion. Furthermore, improvements in one property may come at the cost of another. Therefore, there is no universal material property describing its "quality." In the standard ISO

14044:2006, it is merely noted that changes in the inherent properties of materials may occur during recycling (ISO, 2021). This wording even leaves it open whether these properties are improved or worsened.

Nevertheless, some authors specify decreased material quality through downcycling, which leads to two subcases. The first subcase for this material quality perspective is the *accumulation of tramp elements, impurities, or contaminations* because of downcycling. This perspective is taken by Brooks and Gaustad (2021), Godoy León et al. (2020), Hertwich et al. (2019), Horodytska et al. (2020), Huysman et al. (2015), Jakl and Sietz (2012), Johansson and Krook (2021), Koffler and Florin (2013), Kopnina (2018), Nelen et al. (2014), Singh et al. (2021), Stotz et al. (2017), Valero and Valero (2015), von Gleich et al. (2004), Worrell et al. (2016), and Zhang et al. (2020). According to Baxter et al. (2017), the mere possibility of contamination, without proof, can cause downcycling. One example could be the exclusion by policy of food-grade materials from closed-loop recycling if mixed with any other material at any stage in the material cycle. This definition works without specifying the effects of impurities or contamination on the mechanical or physical properties and environmental resistance. The second subcase for the material quality perspective of downcycling is that *reprocessed materials have a lower value than original materials*. This perspective is taken by Baxter et al. (2017), Friege (2015), Huysman et al. (2015), Kopnina (2018), Kristof and Hennicke (2010), Lèbre et al. (2017), and Ortego et al. (2018a). This definition works without specifying what exactly lead to the reduced material value, which could even come from user perception of recycled materials but comes at the cost of being susceptive to changes in supply and demand.

2.2 | Suitability only for less-demanding applications

The second downcycling perspective is that *reprocessed materials are suitable only for less demanding applications*. This perspective is taken by Bachmann et al. (2018), Benton and Hazell (2013), Binnemanns et al. (2013), Blomsma and Tennant (2020), Cullen (2017), Deckert (2016), Dewulf et al. (2021), Eriksen et al. (2020), Gandenberger et al. (2012), Godoy León et al. (2020), Gößling (2001), Ihnát et al. (2020), Johansson and Krook (2021), Lèbre et al. (2017), Schaubroeck et al. (2021), Valero and Valero (2015), van Eygen et al. (2016), Worrell et al. (2016), and Ziemann et al. (2018). Other than as a physical or technical necessity, this can also occur due to economic rationale, as Cullen (2017) described. This perspective looks particularly at the products fabricated from reprocessed materials, not the reprocessed materials themselves.

2.3 | Use in less-valuable products

A possible consequence of the limited suitability describes the third downcycling perspective in which downcycling leads to the *use of reprocessed materials in products of lesser value*. Nevertheless, this does not necessarily imply lower properties of the material. User perceptions could also cause lower product value. It is an economic evaluation based on prices susceptible to changes in supply and demand. Retreaded car tires are an example of value reduction after recycling despite meeting all necessary material requirements. This perspective is taken by Baxter et al. (2017), Brooks and Gaustad (2021), Borrello et al. (2020), Curtis and Hansson (2019), Despeisse et al. (2012), Di Maria et al. (2018), Friege (2015), Geyer et al. (2016a), Godoy León et al. (2020), Horodytska et al. (2020), Ihnát et al. (2020), Jakl and Sietz (2012), Lèbre et al. (2017), Ortego et al. (2018a), Valero and Valero (2015), Valero et al. (2021), and Zhang et al. (2020).

2.4 | Loss of alloying elements

The fourth downcycling perspective is *alloying elements being lost during the recycling process*. This perspective is taken by Valero and Valero (2015) and Worrell et al. (2016). This perspective on downcycling is closely connected to the term of material dissipation (Helbig et al., 2020), which is the irreversible loss of materials to a receiving medium where recovery is technically or economically unfeasible (Zimmermann & Gößling-Reisemann, 2013).

2.5 | Different material system with no functional use

The fifth downcycling perspective is *reprocessed materials entering a different material system with no functional use*. This perspective is taken by Binnemans et al. (2013), Eckelman et al. (2012), Geyer et al. (2016a), Graedel et al. (2011), Godoy León et al. (2020), Henckens (2021), Ortego et al. (2018b), Tan et al. (2020), and Valero and Valero (2015). Conceptually, this adds another sublevel to the product-material hierarchy by considering material systems. For example, nickel could be used as an alloying element in the material system of stainless steel for tools. However, suppose the scrap leaves the stainless steel system and is recycled for reprocessed carbon steel in the construction sector. In that case, it does not fulfill a functional use because it is not a required alloying element in construction steel and is downcycled according to this perspective.

2.6 | Need of additional virgin material

The sixth and last downcycling perspective is *additional virgin material required to manufacture a product if the starting point were scrap material*. This perspective is taken by Gala et al. (2015), Ortego et al. (2018a), and Worrell et al. (2016). Whether this additional virgin material is required to reduce contaminant content to tolerable levels or to increase the material quality is not essential in this perspective.

2.7 | Summary of the six perspectives

From all these perspectives, it is unclear whether downcycling is meant as an operation, phenomenon, or both. Some perspectives point more toward considering downcycling as an operation of reducing the material quality, mixing materials, using materials in lower applications, or losing elements in the recycling system. In contrast, others consider downcycling as the (undesired) effect of recycling operations, forcing actors to accept lower material quality, higher levels of contaminants, reduced applicability, reduced value of materials or products, or additional virgin material requirements.

The definitions of downcycling by various authors also show an issue in defining the root cause of downcycling. For example, downcycled materials are used in low-value products because their quality is reduced. One could also say the quality of downcycled materials is reduced because different waste materials are mixed or because contaminants cannot be removed in the recycling process. However, one could also say, and thereby close the logical loop, that there is no necessity to address mixing or contamination issues because the reprocessed materials are not meant to be used in the original application. Many of the discussions on reducing downcycling include such hen–egg-problems regarding contaminants. A downcycling spiral with unclear cause–effect chains, if not interrupted, leads to ever-higher levels of contaminants and ever lower-quality applications. Until downcycling is clarified and countermeasures are taken, valuable resources are lost, causing virgin material demand to be higher than necessary. Therefore, we propose a more specific terminology for downcycling.

3 | PROPOSAL FOR A DOWNCYCLING TERMINOLOGY

The perspectives on the downcycling phenomenon were discussed at multiple stakeholder workshops during the research project *OptiMet*, which identified resource efficiency potentials in the metals sector in Germany and Europe for steel, aluminum, copper, and zinc alloys. Experts from the metal-working industry, recyclers, industry associations, NGOs, policy, and academia in Germany participated in the workshops with up to 30 participants. Based on the earlier given literature selection and the stakeholder workshops, we propose the following working definition of the general term "downcycling":

> "*Downcycling* is the phenomenon of *quality reduction* of *materials reprocessed from waste* relative to their original quality, where waste means any substance or object which the holder discards or intends or is required to discard. Downcycled materials count as recycled materials. One can distinguish between thermodynamic, functional, and economic downcycling."

This definition implies that downcycling does not occur on purpose. In contrast, it is an undesired side-effect that can happen during or because of the reprocessing of waste materials. We emphasize the material quality as the main effect of downcycling because this is the most frequent perspective (perspective 1 in the previous section). Nevertheless, all six perspectives mentioned in Section 2 are covered by this definition and can be quantified as thermodynamic, functional, or economic downcycling effects.

Suppose the material quality is reduced because of contamination or mixing effects (perspective 1a). In that case, it is thermodynamically more complex to restore the original properties. Therefore, the criterion for thermodynamic downcycling is fulfilled. The processes leading to downcycling become irreversible when the thermodynamic effort required to restore original properties is so high that it becomes technically or economically unfeasible. Additionally, lower prices are paid for materials affected by contamination or mixing (perspective 1b), fulfilling the criterion for economic downcycling. The restoration of original properties may be so complex that it remains an academic exercise because there may be no practical use in restoring the same original properties. If the thermodynamic effort includes replacing lost alloying elements (perspective 4) or diluting with virgin material, this also addresses the increased virgin material requirements through downcycling (perspective 6).

If the material properties are changed so that less-demanding applications are served with the reprocessed material (perspective 2), this fulfills the criterion for functional downcycling. Less-demanding applications often coincide with products being of lesser value (perspective 3). Many low-value applications have no functional use for high-quality components of reprocessed material, like alloying elements. Therefore, they cause nonfunctional recycling issues (perspective 5). If the material value is reduced (perspective 1b) and potentially even if the product value is reduced (perspective 3), the criterion for economic downcycling is fulfilled.

In summary, this leads to three different opportunities to measure quality reduction: Thermodynamic downcycling, functional downcycling, and economic downcycling, which we here describe qualitatively. *Thermodynamic downcycling* occurs when an increased thermodynamic effort is

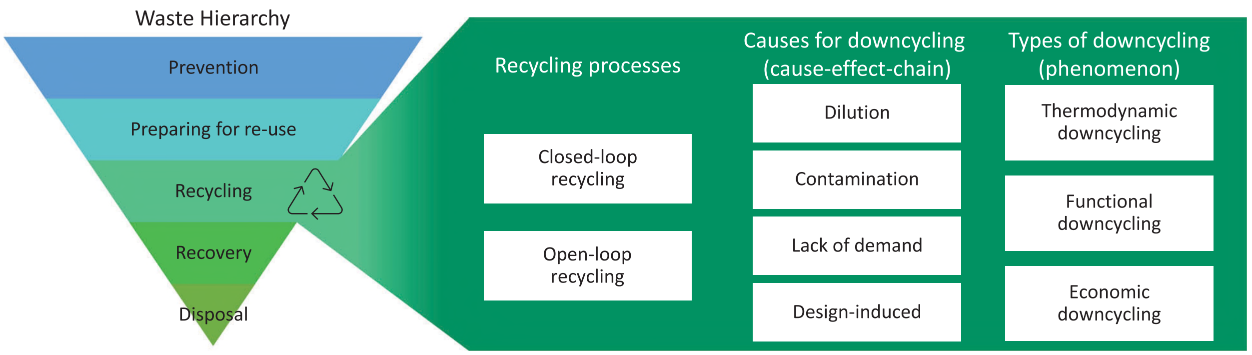

FIGURE 2 Diagram showing recycling processes as part of the waste hierarchy (European Council, 2008) and the causes of recycling processes that lead to various types of downcycling

required to reprocess a material from waste. This thermodynamic effort includes auxiliaries, energy, and heat. For metals, the baseline for comparison is the direct remelting of pure waste at the fabrication stage with the best available technique globally. These terms need to be applied appropriately to other material types, like plastics, natural fibers, and pulp and paper. Reducing thermodynamic downcycling means minimizing this additional thermodynamic effort for reprocessing. *Functional downcycling* occurs if the material reprocessed from waste is suitable for fewer applications than that processed through remelting. Reducing functional downcycling means ensuring materials reprocessed from waste are suitable for many applications. *Economic downcycling* is expressed by a reduced value (usually the price) of a material reprocessed from waste compared to the material processed through remelting. Reducing economic downcycling means maintaining as much value in waste and scrap as possible. Overall, the phenomenon of downcycling is best understood when its different facets are considered: Increased thermodynamic effort, decreased functional applicability, and reduced economic value of waste materials. Quantifying all three downcycling dimensions requires much data that may be difficult to obtain.

Having discussed what downcycling is and how it can be measured does not address the cause of the phenomenon of downcycling. Here, we identify four different causes for downcycling.

Firstly, downcycling can occur because of the *dilution* of high-quality, highly functional, high-value materials caused by joint collection or mixing different scrap types. One example is specialty steels that are not collected separately at the end of life but mixed with other steel scraps. Once mixed, the alloying elements of specialty steels become diluted, and thermodynamic, functional, and economic downcycling may be observed. The dilution of high-quality materials leads to reduced material quality, utilization in less-demanding applications, and the flow of materials into other material systems where they have no functional use (perspectives 1, 2, and 5).

Secondly, downcycling can occur because of the *contamination* with undesired or even harmful substances beyond specific thresholds. For example, if copper-containing scraps like wires are not removed, the copper entering the steel recycling process may impede the steel properties. This contamination causes the need for additional thermodynamic effort for copper removal or dilution with virgin material, application as construction steel with lower value, or selling the reprocessed material as a lower quality class. The contamination of waste materials leads to reduced material quality, utilization in less-demanding applications, and additional virgin material requirements to dilute contaminations (perspectives 1, 2, and 6).

Thirdly and fourthly, downcycling can occur because of a *lack of demand* for recycled materials and *design-induced downcycling*. Technologies are ever-changing, and so are scrap compositions. Suppose a technology that is well designed for closed-loop recycling eventually fades due to market changes or regulation. In that case, for a limited time, there may be no high-value secondary market for its component (lack of demand), and downcycling may then be the only viable option. One example of this is the recycling of cathode-ray tube monitors, particularly their glass components. A closed-loop recycling system existed that declined and ultimately ceased to function when liquid crystal display and plasma display technologies achieved market dominance (Singh et al., 2016).

Moreover, more composite materials that are hardly separable and an ever-increasing variety in the material composition may lead to all the previously mentioned downcycling causes. Materials containing contaminants are more complicated to separate physically, different waste types are more challenging to collect separately, and some markets for specific reprocessed materials may go extinct. Figure 2 schematically displays the causes and types of downcycling.

4 | EXAMPLE

The following brief metal-specific example illustrates different aspects of our downcycling terminology. Terms and definitions might be applied slightly differently in other industries like glass, plastics, natural fibers, or pulp and paper. One of the most frequently used aluminum alloys is the aluminum–magnesium–silicon wrought alloy 6063, one of the hundreds of wrought alloy compositions standardized under EN 573. For example, the

TABLE 1 Elemental content in aluminum alloy 6063 and aluminum scrap of the 6xxx series (DIN, 2003, 2019)

Alloying element (%wt)	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other
6063 alloy (EN 573-3)	97.65-99.35	0.2-0.6	<0.35	<0.1	<0.1	0.45-0.9	<0.1	<0.1	<0.1	each < 0.05; sum < 0.15
6xxx scrap (EN 13920–5)	>97.5	<0.6	<0.5	<0.2	<0.15	<0.5	<0.2	<0.25	<0.1	each < 0.05

alloy 6063 is used for car bodies, and its standardized composition is listed in Table 1 (DIN, 2019). The aluminum alloy content in cars has risen in past decades at the expense of steel content to reduce the weight of the car body (Modaresi & Müller, 2012). In addition to silicon and magnesium, the alloy 6063 can also contain iron, copper, manganese, chromium, zinc, and titanium (DIN, 2019). The thermodynamic realities of aluminum recycling (Nakajima et al., 2010) and the various alloy compositions make closed-loop recycling for aluminum very complicated. It is challenging to remove most alloying elements during recycling because of the high oxidation potential of aluminum, unlike iron or copper (Reuter et al., 2019). Therefore, the typical procedure of aluminum recyclers is to fine-tune the alloying element content of recycled aluminum by mixing different scrap types and, if necessary, diluting these alloying elements with primary aluminum (Løvik et al., 2014). However, primary aluminum is expensive, and its production is energy-intensive. Therefore, alloying element content typically increases with each life cycle of recycled aluminum until scrap is unsuitable for wrought aluminum production and is instead used as secondary material input for cast alloy production.

The wrought alloy 6063 is, in practice, mainly produced from primary metal and preconsumer scraps, with only low content of postconsumer scraps (The Aluminium Association, 2022). One reason for the low postconsumer scrap content is the high demand growth of the aluminum sector in general—in a growing market, the material requirements simply cannot be met entirely with end-of-life scraps from products used in the past. Another reason is the comparatively low alloying element content tolerated in this alloy. Of course, the alloying element content in alloy 6063 is higher than in conducting wires or aluminum foil, which is very pure aluminum. However, it is also much lower than the alloying element content in most cast aluminum alloys (Nakajima et al., 2010). Here we assume the alloy 6063 is produced only from primary metal.

The production of remelted alloy 6063 from uncontaminated, pure alloy 6063 scrap is the baseline for comparing the downcycling. Such a material stream could, for example, occur as cutting residue during fabrication, as preconsumer scrap before the use phase. The thermodynamic effort to simply remelt this pure fabrication scrap to a new alloy can be quantified by simulation (Bartie et al., 2020) or step-wise assessment (Reuter et al., 2005). Small amounts of losses may occur due to surface oxidation. However, overall, the alloy composition does not need to be adjusted by diluting with primary aluminum or re-adding lost alloying elements. Thus, pure 6063 alloy scrap requires low thermodynamic effort for remelting. The function of materials reprocessed from this waste is not impaired, and such a scrap has a comparatively high market value.

If, however, we compare this to postconsumer scrap, taking the alloy scrap of the 6xxx series, standardized under EN 13920–5 (DIN, 2003), as an example, the situation might be very different. Because various alloys of the 6xxx series can all be contained in this scrap type, its chemical composition is less strictly defined, as listed in Table 1. For example, the allowed zinc content in a scrap of the 6xxx series is up to 0.25 %wt, whereas in the 6063 alloy, only 0.1 %wt zinc is allowed (DIN, 2003). In contrast, 6063 alloys may have a higher share of magnesium than is allowed in a mixed 6xxx series scrap (DIN, 2019). Suppose the recycling company has specific scrap origin or product composition information or has made its chemical analyses. In that case, the company may have more precise information about the chemical composition than what is defined in the trade standard.

To produce alloy 6063 by reprocessing mixed 6xxx series scrap, one would observe thermodynamic, functional, and economic downcycling. Thermodynamic downcycling occurs because the higher zinc content necessitates dilution with primary aluminum (or any other low-zinc alloy scrap) and the addition of magnesium during remelting. Functional downcycling may occur in practice because it may be much easier to use the mixed 6xxx series scrap to produce an alloy for which dilution with primary aluminum is unnecessary. For example, Løvik et al. (2014) quantified this effect for automotive aluminum based on the chemical composition of scrap and alloys. They found that dilution of scrap for cast aluminum with the same amount of virgin material would be necessary. For wrought aluminum, four times as much virgin material would be needed for dilution (Løvik et al., 2014). The lower need for dilution in cast aluminum production often implies that the scrap is used for cast aluminum production, which is an irreversible decision substantially narrowing the functions the alloy can fulfill in future lifecycles. Secondary aluminum has, on average, 95% lower GHG emissions intensity than primary aluminum (Van der Voet et al., 2019). Therefore, downcycling still has a significant benefit in greenhouse gas emissions if it reduces primary aluminum use compared to a no-recycling scenario. This substitution of primary production is a central goal of recycling. However, in life cycle assessment (LCA), the substitution potential, or avoided burden, is a composite of the physical resource potential of the waste stream, the recovery efficiency, the substitution ratio, and the market response (Vadenbo et al., 2017; Viau et al., 2020). In this example, if the original wrought alloy 6063 is reproduced, there is no functional downcycling effect. Economic downcycling occurs whenever 6xxx series scrap has a lower price on the scrap market than sorted alloy 6063 scrap, which is plausible because of its less precisely defined chemical composition.

5 | DISCUSSION AND CONCLUSION

This article derives three types of downcycling from six perspectives on the term downcycling in the literature. According to our definition, downcycling is the phenomenon of the quality reduction occurring during or because of recycling, expressing itself in a thermodynamic, functional, or economic way. This definition enables more precision about quality reductions in material cycles. We show that material quality may be reduced because of contamination, dilution, lack of demand, or design-induced downcycling. This quality reduction leads to the three effects of the downcycling phenomenon: Higher thermodynamic efforts for reprocessing of wastes, reduced applicability of reprocessed materials, or reduced economic material value. Downcycling effects occur whenever the conditions for thermodynamic, functional, or economic downcycling are fulfilled. The three types of downcycling do not always all have to be present to fulfill the definition we propose; it may well be that only one type of downcycling is observed while there is no downcycling for the other two types.

Differentiating thermodynamic, functional, and economic downcycling helps find measures that reduce or prevent downcycling. For each type of downcycling, there now exists a clear path to identify and quantify downcycling phenomena. Progress toward a circular economy can be quantified with the thermodynamic effort of recycling, the functional use of secondary materials, and the economic value of materials. A good database on material-specific flows can provide the basis for such detailed assessments and higher transparency for the stock–flow–service nexus in global material cycles. However, current global material flow analyses are often only for a single metal, life cycle inventories do not check mass balances, and large databases for typical scrap compositions are unavailable. Establishing a more comprehensive and reliable database should be a goal of future research projects.

It is not a reasonable goal to reduce downcycling by reducing recycling quantities overall. The waste hierarchy indicates to aim for waste prevention first, followed by preparation for re-use, recycling, recovery, and disposal last, as shown in Figure 2 (European Council, 2008). In many cases, it may be possible to reduce downcycling but not prevent it entirely, leading to a differentiation between avoidable downcycling and unavoidable downcycling. For example, if the best available technique in a recycling sector may lead to some degree of downcycling, but a competing technology or procedure leads to a higher degree of downcycling, the difference between the two practices is avoidable. It is recommended that possible regulations and goals concerning downcycling are aligned with such best available techniques. Even if downcycling is not entirely avoidable, we can still foster high-quality recycling and implement a cascade of slowly and gradually downcycled materials. Quantitatively differentiating between avoidable and unavoidable downcycling requires additional research.

The example of aluminum alloy and scrap recycling is metal-specific. Applying the terms and definitions in other industries needs to align with the terminology and the quantification approach developed within this article. An overspecification for each industry, however, comes at the risk of losing some of the generic aspects derived here from the broad literature.

Finally, avoiding downcycling is not a sustainability target itself, just as recycling is not a target itself. The prevention of downcycling has its limits where sustainability goals are negatively affected. The thermodynamic efforts are closely related to natural resource requirements and energy use. A close link with the method of LCA, which, of course, is a principal method to estimate environmental impacts in recycling, is possible if one succeeds in defining a suitable functional unit. One can then quantify the environmental benefits of avoiding well-defined downcycling phenomena.

Similarly, the quantification of economic downcycling, of course, does not replace cost accounting or economic assessments. Instead, it enables evaluating the cost-saving potentials and economic benefits of establishing more quality-maintaining recycling. The more precise terminology for downcycling developed in this article is, therefore, key to efficient corporate and regulatory actions to identify, quantify, and limit downcycling phenomena. It marks a step into strengthening the circular economy in all material systems and, thereby, reducing virgin material requirements, greenhouse gas emissions, and other environmental impacts caused by material demand.

ACKNOWLEDGMENTS

The authors would like to thank the participants of multiple stakeholder workshops held under the OptiMet project (see Funding information) from 2019 to 2021 for fruitful discussions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Helbig, C., Huether, J., Joachimsthaler, C., Lehmann, C., Raatz, S., Thorenz, A., Faulstich, M., & Tuma, A. (2022). A terminology for downcycling. *Journal of Industrial Ecology*, *26*, 1164–1174. https://doi.org/10.1111/jiec.13289