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Towards a method for poverty reduction potential in social life cycle assessment with application to the cobalt supply chain

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Abstract

Purpose About 8% of the world population lives in extreme poverty. The importance of poverty reduction is acknowledged both in the general sustainability literature and within social life cycle assessment (S-LCA). Existing approaches in S-LCA typically consider the prevalence of poverty, but not how poverty can be reduced. The aim of this paper is therefore to propose a social life cycle impact assessment (S-LCIA) method for poverty reduction potential based on an impact pathway approach.

Methods The basis of the S-LCIA method proposed is a literature review about poverty reduction, primarily in the field of development economics. Based on this literature, an impact pathway and a quantitative S-LCIA method were developed. The S-LCIA method was then applied to the case of the cobalt supply chain to illustrate its applicability, covering production of cobalt hydroxide in the Democratic Republic of the Congo (DRC) and cobalt sulfate in China.

Results and discussion The literature review showed that economic growth is the most important factor for poverty reduction and that no country has escaped poverty without economic growth. This suggests that the value added, the process-level contribution to economic growth, is an important product-related parameter for an S-LCIA method on poverty reduction. However, not all growth benefits the poor, and to capture this, the developed method includes parameters accounting for corruption, inequality, and the share of people living below poverty thresholds. The exemplary case study shows that the potential poverty reduction is higher in the DRC than in China, mainly due to the higher value added generated in the DRC and the larger share of people living in poverty.

Conclusions The developed S-LCIA method constitutes a first attempt at accounting for how products influence poverty, rather than considering the mere prevalence of poverty. It allows for an identification of the largest contributions to poverty reduction, and an analysis of underlying causes in terms of value added, corruption, equality, and poverty levels. Further developments are recommended, particularly regarding estimating the share of the economic growth that actually benefits the poor.

Keywords Economic growth · Inequality · Corruption · Democratic Republic of the Congo · Value added

1 Introduction

Approximately 600 million people, or ca 8% of the world population, are estimated to live in extreme poverty, meaning that they live on < $2.15/day (United Nations 2023). While this is a notable reduction from historical levels at, e.g., > 50% in the early 1900 s, it is still a considerable number of people. Furthermore, the COVID- 19 pandemic constituted a notable setback for global poverty reduction (Hoy and Sumner 2021). "No poverty" is the first of the global sustainable development goals of the United Nations and has been at the core of sustainable development from the start. Already the Brundtland report recommends "overriding priority" to "the essential needs of the world's poor" (WCED

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1987). Considering the many people living in poverty, and the prominent role of poverty in the sustainable development discourse, it is not surprising that poverty has also received attention in the life cycle assessment (LCA) field. Jørgensen et al. (2013) concluded that life-cycle costing (LCC) in its conventional application is poorly related to poverty reduction and instead recommended that social LCA (S-LCA) should cover how product life cycles affect poverty. In line with this, the 2020 Guidelines for S-LCA underlines the importance of fair salaries for workers and poverty alleviation for societies by listing these as so-called subcategories to be assessed in S-LCA (UNEP 2020). Similarly, in a conceptual paper identifying relevant social safeguard subjects for S-LCA, Steen and Palander (2016) proposed poverty as an indicator for assessing several safeguard subjects.

This study considers how to assess poverty reduction in a social life-cycle perspective. The Guidelines for S-LCA outline two approaches to social life cycle impact assessment (S-LCIA): The reference scale approach that focuses on the social performance of companies in a product system and the impact pathway approach that aims at assessing social consequences of a product system (UNEP 2020). Often, the product system is connected to social impacts through an activity variable, which is a measure of process activity that relates to process outputs, commonly workhours or value added. Below, previous attempts at assessing poverty in S-LCA are described for these two approaches.

1.1 Poverty in reference scale approaches

Poverty and related subcategories (e.g., fair salary) have been considered in several S-LCA case studies, applying the reference scale approach, such as Ekener-Petersen and Finnveden (2013), Franze and Ciroth (2011), and Tragnone et al. (2023). When comparing company performance on a reference scale (e.g., from +2 to −2), a baseline level (e.g., zero) needs to be established. Croes and Vermeulen (2016), Falk et al. (2022), and Neugebauer et al. (2014) all estimated fair minimum wages or decent living standards that could serve as such baseline levels. However, when applying the reference scale approach in this way, poverty is seen as a static phenomenon that certain workers or regions experience. For example, Franze and Ciroth (2011) compared cut roses from Ecuador and the Netherlands. They found that the rose production in Ecuador had "very negative" performance regarding fair salary, whereas the Netherlands had "positive" performance. This result should come as no surprise—some countries (e.g., Ecuador) are poorer than others (e.g., the Netherlands), and poorer countries typically have lower salaries.

It may seem logical that activities in poor countries should receive negative poverty impact. However, if S-LCA results are simply based on the current poverty of a country, then the results become predictable and trivial. Such approaches based on the current state cannot be used to assess actual social impacts, i.e., social consequences (Jørgensen et al. 2010; Macombe and Falque 2013). For poverty, state-based approaches miss an important causality: The presence of economic activities can influence poverty to different degrees (Loayza and Raddatz 2010). At worst, results from reference scale approaches, such as unfair salaries and high living wage gaps in poor countries, could be used to motivate moving economic activities to richer countries. While this might improve the reference scale scores of the products assessed, it is questionable if it reduces poverty.

1.2 Poverty in impact pathway approaches

To the best of the authors' knowledge, no dedicated impact pathway approach for poverty has been proposed in the S-LCA field. The 2020 Guidelines for S-LCA also note that little work has been done on assessing positive social impacts like poverty alleviation, particularly regarding impact pathway approaches (UNEP 2020). Still, several impact pathway studies relate indirectly to poverty reduction. Hunkeler (2006) proposed labor hours as a midpoint indicator in S-LCA, since increased labor hours lead to increased income and taxes, and thereby reduced poverty. However, poverty reduction as such was not explicitly assessed. In a series of papers, Weidema (2006; 2018; 2023) outlines a top-down method for assessing wellbeing in terms of quality-adjusted life years (QALY), which implicitly covers a range of impact pathways. It is related to poverty since it considers value added, workhours, and equity weights in the calculation, but is not solely focused on assessing poverty. Another approach, called the living wage gap, considers the additional cost of a product that would have been needed to increase salaries along the product life cycle to a point where the basic needs of workers are fulfilled (Hall 2019, 2021). This calculation is also performed based on the value added in production processes and thus links production processes to a virtual fair salary. However, similar to the reference scale approach, the living wage gap gives higher impact to poor people by default, since the gap between salaries and sufficient living wages is generally higher for the poor. How the production processes influence poverty is thus not covered.

1.3 Aim of the study

As described above, reference scale approaches generally neglect how products influence poverty, and there is a lack of impact pathway approaches focusing on poverty. The aim of this study is to propose an S-LCIA method based on impact pathways for how product life cycles can potentially reduce poverty, addressing the subcategory "poverty alleviation" in the 2020 Guidelines for S-LCA (UNEP 2020). To this end, we provide a brief overview of the literature on poverty reduction, mainly from the field of development economics. We then derive characterization factors through which these insights can be operationalized into S-LCA. Finally, we apply the proposed method to the case of cobalt supply, which involves artisanal (small-scale) cobalt mining in the southeastern Democratic Republic of the Congo (DRC). This is an interesting case from a poverty perspective, since it is a sector noted for its many poor workers (Amnesty International 2016; Carter and Sturmes 2020), but also a sector that has been claimed to have the potential to reduce poverty in the region (Sovacool 2019; Tsurukawa et al. 2011).

Previously, studies assessing poverty along the cobalt supply chain have applied the reference scale approach or more aggregated social assessment methods. Thies et al. (2019) assessed a cobalt-containing lithium-ion battery pack using a reference scale approach for four social impacts, among them poverty. They concluded that the risk of poverty is highest in poor countries where raw material extraction (e.g., cobalt) and component production take place. Mancini et al. (2021) assessed 14 non-poverty social impacts of artisanal mining in the DRC using the reference scale approach and discussed miner's income qualitatively, concluding that more research is needed on artisanal mining incomes. Bamana et al. (2021) identified barriers and opportunities for data collection in S-LCA of artisanal cobalt mining in the DRC. They discussed fair salaries qualitatively and noted that artisanal miners typically lack set salaries and are often subject to rigged price settings. Finally, Orola et al. (2022) assessed the cobalt mining in the DRC using the wellbeing-adjusted life years (WELBY) indicator, which is an aggregated measure of social wellbeing. Fair salary was included in the aggregated assessment but not discussed as a separate issue.

2 Overview of poverty reduction

Poverty is characterized by persistence—once in poverty, it is challenging to become richer (Balboni et al. 2021). For example, if someone is too poor to pay for healthcare, and becomes too ill to work, the person can become even poorer due to the lack of income. In cases where incomes below a certain level are insufficient to escape poverty and instead converge back to the lower income level, this can be referred to as a poverty trap (Banerjee and Duflo 2011; Kraay and McKenzie 2014). Finding ways to escape this stagnation is thus key to poverty reduction.

In a TED talk, Rosling (2007) from the Gapminder organization differs between *means* and *goals* when it comes to socioeconomic development. He lists human rights and culture as the most important *goals* of development, followed by health. He then lists economic growth as the most important *mean*, followed by governance and education. No country, he argues, has escaped poverty without economic growth. He also makes the important remark that economic growth, governance, and education are not important if interpreted as end goals—they have little value in themselves unless they lead to progress and development.

Rosling is not alone to highlight economic growth as an important mean towards poverty reduction. The Nobel laurates Abhijit Banerjee and Esther Duflo (2020) agree on the value of economic growth as a mean towards poverty reduction, rather than an end. Vásquez (2001) also agrees on the importance of economic growth, stating that "the single, most effective way to reduce world poverty is economic growth." Three economists writing for the British Department for International Development (2015) concur that economic growth is the single most important way to pull people out of poverty, mentioning that 10% increased average income typically gives 20–30% lower poverty. Many other authors also highlight economic growth as the key to poverty reduction, e.g., Hoy and Sumner (2021), Besley and Burgess (2003), Tsai and Huang (2007), Dollar et al. (2016), Pegg (2006), and Loayza and Raddatz (2010). Examples of poverty reductions due to economic growth can be found across the globe, from China to Mozambique. Factors closely related to economic growth, such as business-friendly regulation that encourages start-up companies (Djankov et al. 2018), macroeconomic stability (Ames et al. 2001), and trade (Bhagwati and Srinivasan 2002), are also brought up in the literature as ways to reduce poverty via economic growth.

However, it is also clear that economic growth is not the sole influencing factor. While economic growth seems to be a necessary condition, it is not in itself a guarantee for poverty reduction, as increased poverty has been observed also in countries with economic growth (Ayoo 2022). This can be referred to as poverty elasticity, the rate at which poverty changes given changes in economic growth, which differs between regions (Besley and Burgess 2003). For growth to reduce poverty most efficiently, it must be targeted towards the poor though social policies, i.e., be "inclusive" or "pro-poor" (Ayoo 2022; Hoy and Sumner 2021). Consequently, growth can reduce poverty more if it happens in regions where such policies are present, which relates to the governance factor listed by Rosling (2007). The Department for International Development (2015) report states that high inequality in a country reduces the efficiency by which growth reduces poverty, as shown by, e.g., Ravallion (2005). Besley and Burgess (2003) also regard reduced inequality as a prerequisite for reducing poverty and show that the magnitude of this effect varies notably across regions. Particularly for poor people living in middle-income countries, like China and Mexico, inequality rather than lacking growth might not be the main hinder for poverty reduction (Page and Pande 2018). Specifically, several authors recommend investing revenues from economic growth into education as a mean to reduce poverty (Banerjee and Duflo 2020; Besley and Burgess 2003), as also pointed out by Rosling (2007).

Sometimes, other factors are also listed as important to reduce poverty, such as health care, clean water, and sanitation (see, e.g., Pan et al. (2021)). However, while these factors are arguably part of a wealthy life, the lack of them is primarily a "manifestation" of poverty (Ayoo 2022), and they are not means of escaping it. Calling for such factors to reduce poverty thus becomes akin to the fabricated suggestion, erroneously attributed to Queen Marie Antoinette after her death, that the hungry Parisians in the 1700s should eat cake to reduce their hunger. However, since most Parisians at the time were poor, they did not have access to cake. And like lack of cake, the lack of health care, clean water, and sanitation are not likely to vanish before poverty reduction means have been implemented.

In summary, to reduce poverty, economic growth is most important, but it needs to be efficiently directed towards investments that reduce poverty. With too high inequality or similar social issues, the economic growth might not have the poverty-reducing effect anticipated.

3 Poverty reduction in S-LCIA

We believe the distinction between means and goals proposed by Rosling (2007) is important for impact pathways on poverty reduction potential in S-LCIA. Rather than focusing on whether the goals (e.g., fair salaries) have already been achieved, an S-LCIA method could focus on the means—that is, to which extent the product contributes to reaching the goals. An analogy to environmental LCA can be made here, where LCIA of climate change impacts typically does not consider whether climate goals are met, but rather the contribution of the product to climate change. However, poverty is a complex phenomenon (Banerjee and Duflo 2007, 2011), and Croes and Vermeulen (2016) note that "because impact pathways related to income issues are extremely complex […], it will be quite a challenge to present an accurate pathway-derived measure for sub-fair wages." Acknowledging this complexity, an S-LCIA method for poverty reduction potential needs to rely on general models and insights, similarly to LCIA methods in environmental LCA. For example, environmental LCIA methods for eutrophication at the midpoint level rarely account for detailed impacts in certain areas, such as specific species in the Baltic Sea. Below, an S-LCIA method is outlined based on these considerations and the insights from Section 2. The impact pathway it builds on is outlined together with the input parameters in Fig. 1.

3.1 Value added as basis

Given the knowledge described in Sect. 2, it stands clear that economic growth is an important mean to include in an S-LCA method for indicating the poverty reduction potential of a product. Economic growth in terms of gross domestic product (GDP) can be measured in three ways: (i) Total value added from goods and services produced, (ii) total income generated by employees and businesses, and (iii) total value of expenditures, businesses, and governments on final goods and services. To assess the influence of a process or product on poverty, approach (i) is most relevant, where the GDP is calculated as the sum of all value added (*VA*) in a region *i*:

$$\mathrm{GDP_i} = \sum\nolimits_{\mathrm{i}} \mathrm{VA_i} \tag{1}$$

The VA is, in turn, the difference between the market value of a product or service output from a transformation process, and the market value of all inputs to the

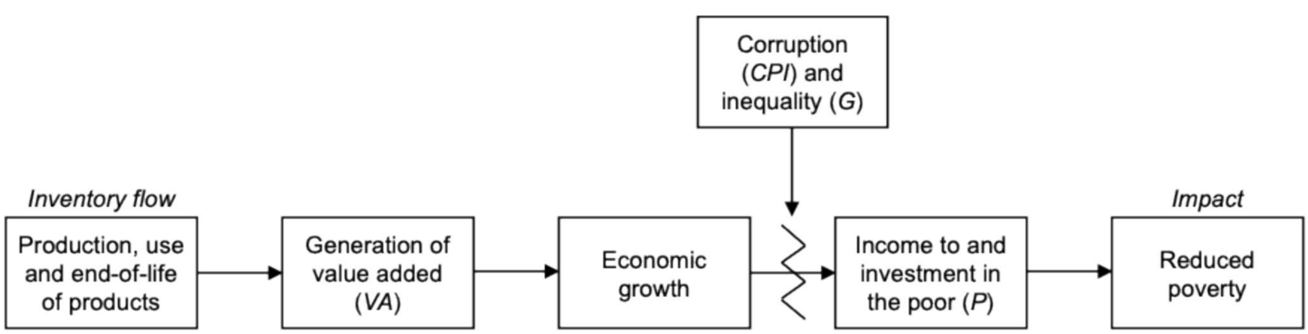

Fig. 1 The impact pathway covered in the developed S-LCIA method. Production, use and end-of-life refer to the stages of product life cycles modelled in LCA studies, which contain inventory flows that can generate value added. Corruption and inequality are factors that can break the impact pathway. The input parameters to the S-LCIA method are also shown: VA = value added, CPI = corruption perception index, *G* = Gini coefficient, *P* = share of people living in poverty

transformation process (i.e., its production costs). The VA thus emanates from transformation processes, which is also what is captured in many of the unit processes of a product system in LCA (see generation of value added in Fig. 1). The Department for International Development (2015) write that poverty gets reduced by a certain factor given an increase in economic growth, which suggests a proportional relationship between poverty reduction and growth. It thus seems reasonable that a CF for poverty reduction potential (CF_{PRP}) should be proportional to the VA generated in process *j*:

$$CF_{PRP} \propto VA_j \quad (2)$$

As mentioned in Sect. 1.2, VA has been applied as a foundational input parameter in several other impact pathway approaches related to poverty as well (Hall 2021; Weidema 2018). However, it is clear from Sect. 2 that for economic growth to reduce poverty efficiently, it needs to be pro-poor. Mathematically, this can be translated into a share factor *S* that determines the share of the growth that benefits the poor in region *i*:

$$CF_{PRP} = VA_j \times S_i \quad (3)$$

S is challenging to estimate, particularly for many processes. Much economic growth benefits the poor indirectly, for example, through taxation and subsequent government investments in infrastructure and education. In Sect. 3.2, we highlight some factors that are important for *S*.

3.2 Factors for pro-poor growth

We explore three factors that can hinder economic growth from leading to poverty reduction: Corruption, inequality, and lack of poor people. First, if all the *VA* in region *i* is lost due to corruption (i.e., bad governance), then none of the growth will benefit the poor, as illustrated in Fig. 1. A common indicator for measuring the level of corruption in a country is the corruption perceptions index (CPI), which ranks countries by their perceived level of public sector corruption on a scale from 0 to 100 (Transparancy International 2024). Countries with low corruption, such as Denmark and New Zealand, have CPI > 80, while countries with high corruption, such as Somalia and Syria, have CPI ≈ 10.

Second, as highlighted in Section 2, inequality is a factor that lowers the poverty reduction potential. If there is total inequality in region *i*, then the share of the *VA* generated that benefits the poor will again be zero, as illustrated in Fig. 1. Income inequality is often measured by the Gini coefficient of a region *i* (G_i), which considers the difference between people's income relative to the mean. The Gini coefficient ranges between 0 and 1, where 0 means perfect equality and 1 means maximum inequality. In practice, the Gini coefficient varies between about 0.2 for countries with low inequality (e.g., Norway) and about 0.6 for countries with high inequality (e.g., South Africa). Since a CF for poverty reduction potential reflects positive social impact, low inequality (e.g., a low Gini coefficient) should lead to a high CF.

Third, if there are no poor people in region *i*, then the share of the *VA* that benefits the poor will also be zero (see income to and investments in the poor in Fig. 1). Increasing growth by 1 USD per person and day in a high-income country like Canada reduces poverty less since there are fewer poor people there. Conversely, doing so in a low-income country like Cameroon might have a notable influence. To quantify this, the share of people living in poverty in region *i* (P_i) can be applied. Such poverty rates can be based on different poverty thresholds in terms of income earned per day. The World Bank sets such threshold values to 2.15, 3.65, and 6.85 USD/person and day, for three different levels of poverty, where the first reflects "extreme poverty." For such extreme poverty, the share of people living under the threshold typically ranges from close to zero in high-income countries to > 0.5 in some African countries.

While the CPI, Gini coefficient, and share of people living in poverty do not fully capture *S* in every possible aspect, they are arguably important constituents of *S* that relate strongly to the governance aspects highlighted in Section 2. Together, they allow for a social analysis of the VA of a certain process by answering questions about (i) whether the VA is lost due to corruption, (ii) whether the VA is evenly distributed across incomes, and (iii) whether there are any poor people in the region that can benefit from the VA. Also, there are numerical estimates accessible for all three parameters for most countries in the world. For example, the Gapminder (2019) organization provides data on poverty and the Gini coefficient, and the CPI is published by Transparancy International (2024). Mathematically, the three factors can be combined and inserted as a proxy for *S* in Eq. 3, yielding:

$$CF_{PRP} = VA_j \times \frac{CPI_i}{100} \times (1 - G_i) \times P_i \quad (4)$$

In Eq. 4, 1 minus the Gini coefficient is applied, so that countries with low inequality (low Gini coefficient) get a high CF_{RPR}. Also, the CPI is divided by 100 to obtain a fraction between 0 and 1, similar to the poverty rate and Gini coefficient. Essentially, Eq. 4 is a so-called Fermi estimation, with a similar build-up as the Drake equation used to predict the number of extraterrestrial civilizations in the Milky Way Galaxy by first estimating the number of stars and life-supporting planets (corresponding to *VA* here), and then multiplying by a series of fractions for, e.g., planets that can support life, develop intelligent life, and release detectable signs of their existence (corresponding to $CPI_i/100$, $1-G_i$, and P_i). Figure 2 illustrates Eq. 4 and its rationale graphically.

3.3 Considerations for interpretation

The suggested CF in Eq. 4 has the unit USD/output and should be multiplied by the physical outputs of processes along the life cycle to calculate the poverty reduction impact. Thus, the CF should not be multiplied by elementary flows as is common for most environmental impact categories (ISO 2006), but rather with an economic product flow, which thus constitutes the activity variable for the developed S-LCIA approach. For more details on this difference, see Heijungs (2024). Furthermore, the S-LCIA method for poverty reduction potential proposed reflects a positive social impact, meaning that high values are preferable. This is opposed to the more common assessment of negative impacts in environmental LCA and S-LCA, where low values are preferable. See further Di Cesare et al. (2018) for a review on positive impacts in S-LCA. It can also be noted that the CF in Eq. 4 reflects a longer-term perspective on poverty reduction, where well-directed economic growth slowly builds up towards an eventual escape from poverty over time periods such as years or decades, similar to long-term perspectives on resource depletion in environmental LCA (Drielsma et al. 2016). The effects on poverty from more short-term efforts, such as corporate social responsibility, are not considered. (Furthermore, such short-term efforts often have limited effects on reducing poverty—see, for example, Banerjee (2008).)

4 Case study on cobalt supply

The proposed S-LCIA method for poverty reduction potential was tested in a case study on cobalt supply from the DRC and China, ending with the battery material cobalt sulfate (Fig. 3). This represents the globally most common cobalt supply route, with the DRC providing approximately 60–70% of all cobalt mined (OECD 2019) and China having control over approximately 85% of all battery-grade cobalt sulfate production (Gulley 2024). The main data sources for descriptions of this supply chain are Kara (2023), Dai et al. (2018), and Das et al. (2024), of which the two former performed site visits and the latter a literature study. As shown in Fig. 3, the cobalt supply chain in the DRC is complex. While crude cobalt hydroxide is the main material exported, it does not constitute 100% of the exports. In 2019, the DRC reinstated their ban on exports of cobalt concentrates directly from mining (Hunter 2019), but the Congolese government still allows some mining companies to continue shipments of concentrates (Jamasmie 2021). However, the case study considers only the cobalt hydroxide exported. Also, separating artisanal mining and industrial (large scale) mining in practice is challenging, since there are many instances along the supply chain where the artisanal and industrial ores are combined (Kara 2023). The artisanal miners can pay to access industrial sites and sell their ore through negociants and depots, after which the ore is bought back by the industrial mines or by a cobalt hydroxide refinery and treated like industrially mined ore. It is here assumed that 80% of the cobalt mined in the DRC is industrial (Al Barazi et al. 2017), since such an assumption is required to distribute the diesel and water inputs in industrial cobalt mining over an average cobalt mined in the DRC.

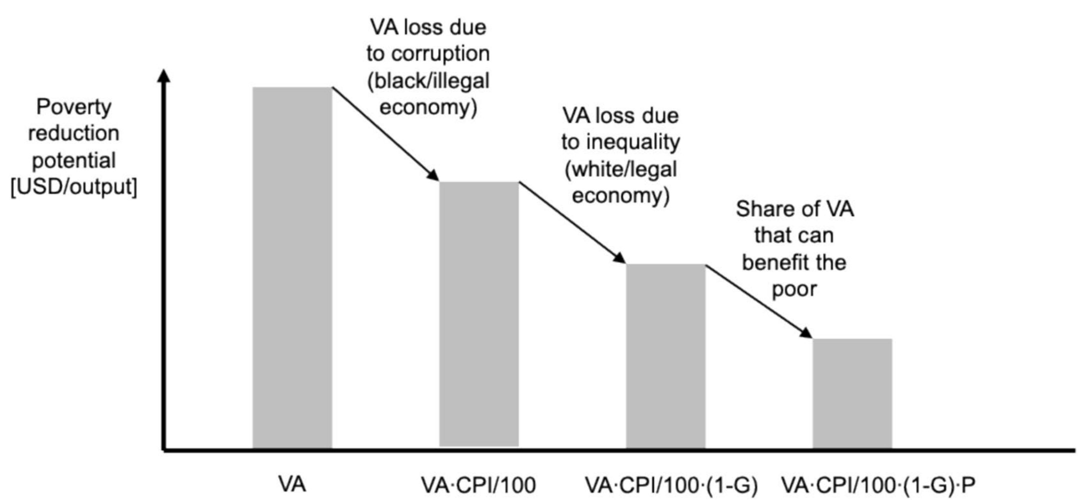

Fig. 2 Illustration of Eq. 4 and the rationale behind the included parameters. VA stands for value added (USD or other currency), CPI for the corruption perceptions index (–), G for the Gini coefficient (–), and P for the share of poor people in a region (–)

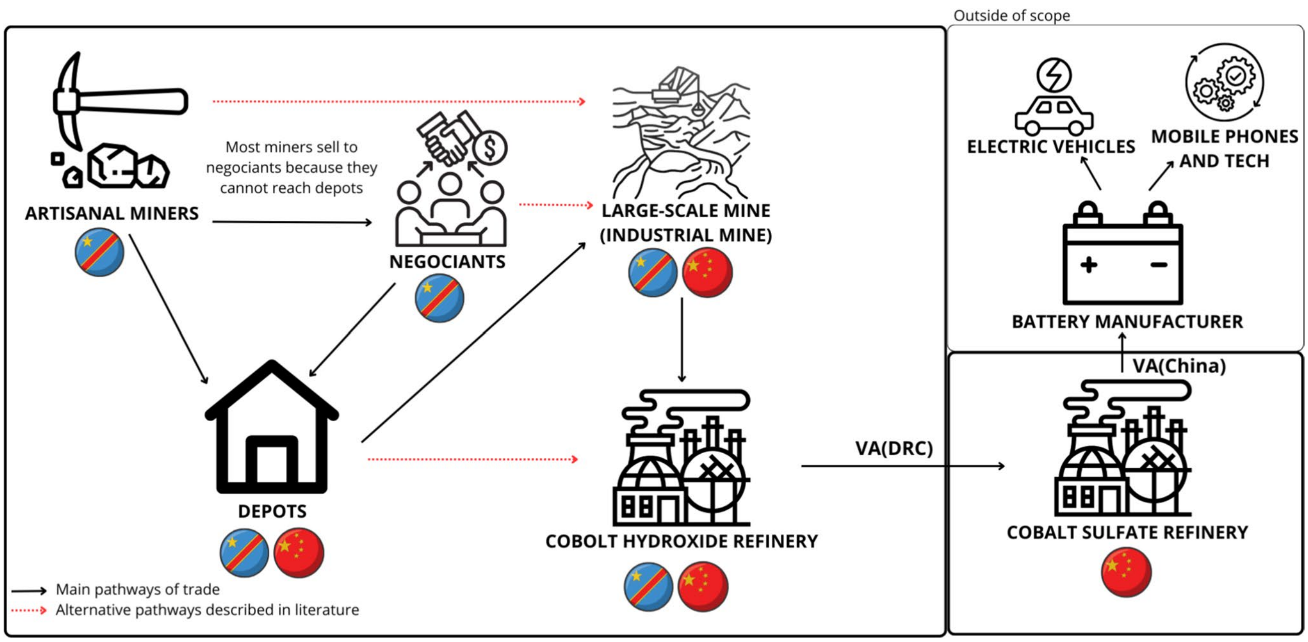

Fig. 3 Flow chart showing the cobalt supply chain under study. The two aggregated processes considered in the modeling are surrounded by thicker frames. The flags symbolize under which authority the process occurs. VA = value added, DRC = Democratic Republic of the Congo. Figure drawn based on descriptions by Ritchie (2023), Kara (2023), and the World Bank (2021)

In addition to the product system described in Fig. 3, a scenario with cobalt sulfate refining in Finland instead of China was considered. Finland is the only European country with such industrial capacity and illustrates the developed method for a high-income country.

4.1 Physical flow inventory

As a first step, the physical flows that link the product to potential reduction of poverty must be inventoried. Only the cobalt hydroxide and sulfate materials were considered, since preliminary calculations indicate they account for 80–90% of the VA. This is because the other inputs are generally low-value products, such as water, bulk chemicals (e.g., sodium hydroxide), and common fossil fuels (e.g., natural gas), and are applied in modest amounts in the two considered processes. The flows are based on the cobalt sulfate supply data published by Dai et al. (2018) for the GREET model. As can be seen in Table 1, the data effectively represents a 100% cobalt yield in the cobalt sulfate production process. Although this is likely optimistic, it was deemed a sufficient proxy as there is no reason to believe the yield should be much lower.

4.2 Value-added calculation

The next step is to gather price data for calculating the VA. Doing so for cobalt brings a number of challenges. First, prices can be reported either per tonne of material (cobalt hydroxide or sulfate) or on a 100% cobalt contained basis. Second, price data is adjusted for inflation coupled to the publishing year, and the method behind this adjustment is often not declared. Thus, depending on the year of the publication, prices published in different years from the same source can differ even when they represent the same year and commodity. To overcome these challenges, we gathered all data from one single source—a news report published by Stockhead containing price data from Benchmark Minerals

Table 1 Mass flow inventory for cobalt hydroxide and cobalt sulfate production. Co eq stands for cobalt equivalents, i.e., cobalt content. Data from Dai et al. (2018)

Material	Mass (kg)	Cobalt content	Mass (kg Co eq)
Cobalt mining and crude cobalt hydroxide production in the DRC*			
Crude cobalt hydroxide, output	2.86	35%	1
Cobalt sulfate production in China			
Crude cobalt hydroxide, input	2.86	35%	1
Cobalt sulfate, output	4.88	20.5%	1

*The copper-cobalt ore input to the crude cobalt hydroxide production is extracted from nature and thus considered to have zero value in the value added calculation. Therefore, it is not included in this inventory

Table 2 Four-year average prices of cobalt hydroxide and cobalt sulfate for the years 2018–2021, reported in the monetary value of 2021, based on data from Adams (2022). Co eq stands for cobalt equivalents, i.e., cobalt content

Year	Cobalt hydroxide (US $/kg Co eq)	Cobalt sulfate (US $/kg Co eq)
2018	61.5	78.7
2019	22.0	35.0
2020	23.9	35.0
2021	46.1	59.7
Average	38.4	52.1

Intelligence (Adams 2022). A graph in this report provides price data on 100% cobalt contained basis for both cobalt hydroxide and sulfate over several years, with the same correction factor for inflation. Values were retrieved from the graph using the WebPlotDigitizer software (https://automeris.io, version 5). Based on the retrieved values, 4-year price averages for the time 2018–2020 were calculated (Table 2). In general, we recommend 5-year averages to even out price fluctuations (which have been considerable for cobalt), but unfortunately, only 4 years of price data are included in the abovementioned report.

Next, the *VA* can be calculated from the prices (x) as described in Sect. 3.1:

$$\mathrm{VA}_{\mathrm{Co(OH)_2}} = x_{\mathrm{Co(OH)_2}} - 0 = 38.4 - 0 = 38.4 \quad (5)$$

$$\mathrm{VA}_{\mathrm{CoSO_4}} = x_{\mathrm{CoSO_4}} - x_{\mathrm{Co(OH)_2}} = 52.1 - 38.4 = 13.7 \quad (6)$$

where $Co(OH)_2$ and $CoSO_4$ stand for cobalt hydroxide and sulfate, respectively. An alternative option would have been to calculate the VA using an economic input–output model, such as EXIOBASE 3 (Stadler et al. 2018). However, these typically have low resolution regarding product categories and geographical regions. For this case, all of Africa except for South Africa is in EXIOBASE 3 grouped together into "Rest of the World – Africa," and the most suitable product group for cobalt sulfate would probably be "chemicals nec," which contains a wide range of chemicals. Such approximations might be acceptable for minor inputs to a larger product system, but are not deemed sufficient for the more detailed analysis of cobalt sulfate supply attempted in this study.

4.3 Poverty reduction potential calculation

Gini coefficients and shares of people in poverty, for different poverty thresholds (2.15, 3.65, 6.85 USD/day), were obtained from Gapminder (2019) since their database provides consistent data across the years 2018–2021 for the DRC, China, and Finland. Gini coefficients in that database are gathered from different sources and extrapolated to cover years without data. We verified this data by comparing to available Gini coefficients for the years 2018–2021 from the World Bank (2023). Note that the values for the parameter P_i are adjusted compared to the raw data from Gapminder (2019), as it reports the share of the population *not* living below each poverty threshold. Values for the *CPI* were obtained from Transparancy International (2024). Table 3 shows the 4-year average values for the parameters CPI_i, G_i, and P_i applied in the calculation of the share factor S according to Eq. 4.

S was then calculated as an average over 2018–2021, to match the 4-year average of the VA. Table 4 reports this 4-year average value of S depending on the poverty threshold applied for the two countries studied.

The CF_{PRP} was then calculated for the three poverty shares for cobalt hydroxide and sulfate:

$$\mathrm{CF}_{\mathrm{PRP,Co(OH)_2}} = \mathrm{VA}_{\mathrm{Co(OH)_2}} \times S_{\mathrm{DRC}} \quad (7)$$

$$\mathrm{CF}_{\mathrm{PRP,CoSO_4}} = \mathrm{VA}_{\mathrm{CoSO_2}} \times S_{\mathrm{China}} \quad (8)$$

$$\mathrm{CF}_{\mathrm{PRP,CoSO_4}} = \mathrm{VA}_{\mathrm{CoSO_2}} \times S_{\mathrm{Finland}} \quad (9)$$

Table 5 reports the resulting CF_{PRP} values for the DRC, China, and Finland, which differ depending on the poverty threshold applied.

The CFs in Table 5 can be multiplied with the mass flows in Table 1 (Co eq values, but can also be converted to kilogram material) to obtain the potential poverty reduction for

Table 3 Gini coefficients (G), CPI values, and poverty shares (P) with three thresholds for the DRC, China, and Finland (Transparancy International 2024; Gapminder 2019)

Parameter	2018	2019	2020	2021
G_{DRC}	0.579	0.579	0.567	0.553
CPI_{DRC}	0.20	0.18	0.18	0.19
$P_{DRC, 2.15}$	0.774	0.759	0.78	0.772
$P_{DRC, 3.65}$	0.894	0.901	0.911	0.907
$P_{DRC, 6.85}$	0.967	0.969	0.972	0.971
G_{China}	0.615	0.615	0.609	0.609
CPI_{China}	0.39	0.41	0.42	0.45
$P_{China, 2.15}$	0.007	0.003	0.002	0.001
$P_{China, 3.65}$	0.058	0.039	0.028	0.019
$P_{China, 6.85}$	0.284	0.253	0.252	0.207
$G_{Finland}$	0.727	0.727	0.727	0.727
$CPI_{Finland}$	0.85	0.86	0.85	0.88
$P_{Finland, 2.15}$	0	0	0	0
$P_{Finland, 3.65}$	0.001	0	0	0
$P_{Finland, 6.85}$	0.002	0.001	0.001	0.001

the two respective materials at three alternative poverty levels. The results are shown in Fig. 4. These values can also be summed for the cobalt sulfate supply chain (DRC + China or DRC + Finland) and compared to other supply routes for cobalt sulfate.

4.4 Results interpretation

Figure 4 suggests that the cobalt hydroxide production in the DRC has a bigger potential for poverty reduction than the cobalt sulfate production in China. The relative difference varies depending on the poverty threshold. For 2.15 USD/day, it is approximately a factor of 300, while for 3.65 USD/day, it is approximately a factor of 30, and for 6.85 USD/day, it is approximately a factor of 5. This is mainly because of the higher VA generated in the DRC (almost a factor of three) and the higher share of poor people in the DRC. For extreme poverty (2.15 USD/day), the share is much higher in the DRC compared to China, but for the 6.85 USD/day threshold, the relative difference is lower, although the DRC is still notably higher than China. The DRC has been ranked among the ten poorest countries in the world (Ventura 2024), while China is close to the median and often considered a middle-income country. The Gini coefficient is similar between the DRC and China at approximately 0.6 (Table 3). This highlights that richer countries are not necessarily much more equal than poorer countries. While China has seen a massive reduction in poverty since the 1970s, inequality has also increased, albeit more slowly (Piketty et al. 2019). The CPI differs by a factor of two in favor of China, which is reasonable considering that corruption shows a strong correlation with poverty (Ambraseys and Bilham 2011).

Table 4 Calculated *S* values (4-year average), defined at different thresholds for income per day

Parameter (average 2018–2021)	Cobalt hydroxide production in the DRC	Cobalt sulfate production in China	Cobalt sulfate production in Finland
S, defined at 2.15 USD/day ($S_{2.15}$)	0.081	0.00081	0
S, defined at 3.65 USD/day ($S_{3.65}$)	0.096	0.0090	0.00015
S, defined at 6.85 USD/day ($S_{6.85}$)	0.10	0.063	0.00078

Table 5 Characterization factors for potential poverty reduction (CF_{PRP}), defined at different thresholds for income per day. Co eq stands for cobalt equivalents, i.e., cobalt content

Characterization factor (USD/kg Co eq)	Cobalt hydroxide production in the DRC	Cobalt sulfate production in China	Cobalt sulfate production in Finland
CF_{PRP}, defined at 2.15 USD/day	3.1	0.011	0
CF_{PRP}, defined at 3.65 USD/day	3.7	0.12	0.0021
CF_{PRP}, defined at 6.85 USD/day	4.0	0.87	0.011

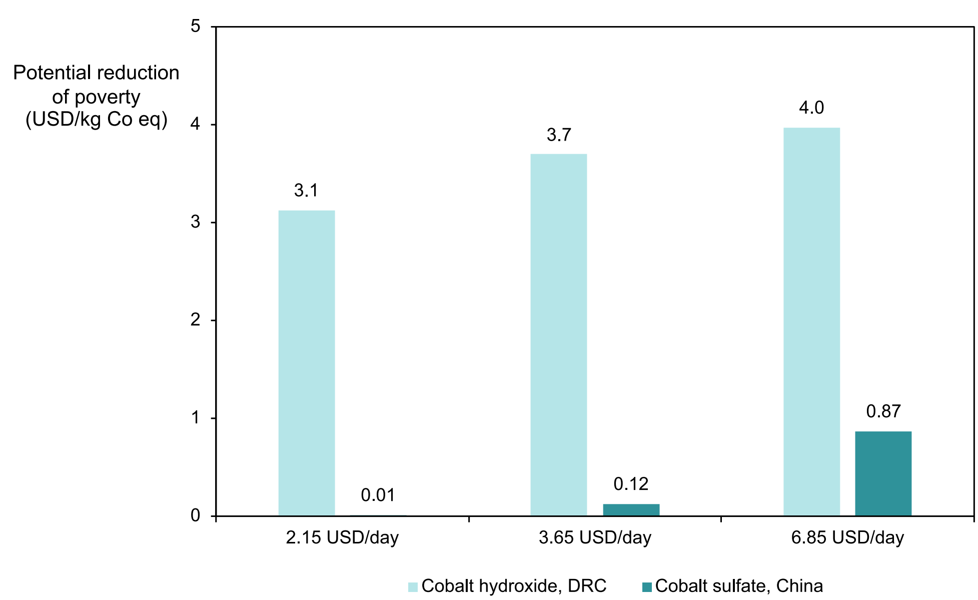

Fig. 4 Results for potential reduction in poverty for cobalt hydroxide produced in the Democratic Republic of the Congo (DRC) and cobalt sulfate produced in China. Results are shown on a cobalt content basis for three different poverty thresholds

These results are broadly in line with other sources pointing to the potential of (artisanal) cobalt mining to reduce poverty in the DRC (Sovacool 2019; Tsurukawa et al. 2011). However, it is possible that the potential poverty reduction calculated here for the DRC constitutes an overestimation. In the DRC, eight of the 14 biggest cobalt mines have Chinese owners (World Bank 2021). Most depot owners are also Chinese and have been accused of offering below-market prices to artisanal miners and negociants (Kara 2023). Most larger cobalt refineries in the DRC are also Chinese-owned (World Bank 2021). The Chinese in the DRC tend to live in separate communities and hire their countrymen to more qualified positions, and there are suspicions that the companies underreport revenues to avoid paying taxes (Kara 2023). It is thus likely that a notable share of the potential economic growth is lost from the DRC to Chinese actors. In addition, the significant number of migrant workers from the nearby country of Zambia means that some of the monetary flows contributing to growth likely end up there. However, a comprehensive assessment of all monetary flows lost to countries such as China and Zambia is challenging due to lack of data and secrecy.

Thus, the poverty reduction indicator developed identifies a potential to reduce poverty particularly in the DRC, while additional factors might prevent this potential from becoming realized. This potential can be realized by ensuring that the VA benefits the poor no less than what is possible given the current state of corruption and inequality. This includes that mining and refining workers in the DRC are paid market prices for the cobalt mined and refined. As reported by Kara (2023), Chinese owners of mines and refineries in the DRC have an important role in this realization. The poverty reduction potential can increase further if corruption and inequality in the DRC is reduced, that is, if a larger share of the VA is directed to the poor. This task mainly falls on the Congolese government and its agencies, such as the state-controlled company Gécamines, which is heavily involved in cobalt exploration, research, and production. It has furthermore been proposed that due to poverty and other social issues, downstream supply chain actors should not purchase cobalt from the DRC, for example, to their battery production (Sharma and Manthiram 2020). However, reducing cobalt trade in the DRC would reduce the VA generated and thus the poverty reduction potential and is therefore not recommended based on the results of this study.

A remark can be made regarding the comparatively low VA for cobalt sulfate production in China. Clearly, the VA is lower for converting cobalt hydroxide into cobalt sulfate, than for converting copper-cobalt ore to cobalt hydroxide. However, cobalt sulfate is not the end product of this value chain. The produced cobalt sulfate is an important precursor material for producing nickel-manganese-cobalt (NMC) batteries, a type of lithium-ion battery. If the analysis would have covered this step as well, it would likely show higher VA. However, this would have made the analysis more complex, since a number of additional battery materials are required to produce an NMC battery.

When changing location from China to Finland, the potential to reduce poverty in the cobalt sulfate refining is reduced to negligible levels (zero, 0.002, and 0.01 USD/kg cobalt content for the respective poverty thresholds—compare to Fig. 4). This is partly due to lower corruption, but mostly due to much lower poverty. The reported share of the population living below 2.15 USD/day in Finland is zero, giving no potential to reduce poverty at all for that poverty level. This is in line with the inherent assumption in the developed method that without poverty, there is no potential for poverty reduction. Contrary to reference scale approaches, which typically highlight hotspots with unfair salaries, the developed method highlights hotspots where the potential to reduce poverty is high.

Considering the notable variation in prices, we performed a sensitivity analysis by considering the highest and lowest price difference between cobalt hydroxide and sulfate over the 2018–2021 time period. The highest was in 2018, and would give a *VA* at 61 USD/kg Co eq for cobalt hydroxide and 17 USD/kg Co eq for cobalt sulfate. The lowest was in 2020 and would give a *VA* at 24 USD/kg Co eq for cobalt hydroxide and 11 USD/kg Co eq for cobalt sulfate. The variation is thus a factor of three at most (for cobalt hydroxide) and does not change the main conclusion of the study.

5 Discussion

While the developed S-LCIA method only assesses *potential* poverty reduction, it constitutes a step forward in the assessment of poverty reduction in S-LCA. Rather than seeing the presence of poverty itself as a negative social impact, as with the reference scale approach, it considers opportunities for reducing poverty. In line with the 2020 Guidelines for S-LCA (UNEP 2020), the developed S-LCIA method assesses poverty reduction on a societal level, specifically for the countries included in the product system. Thus, companies could apply this method to investigate and compare the poverty reduction potential of their products beyond their own employees and employees in their upstream supply chains.

Still, there is room for developing this S-LCIA method further, particularly regarding the share of the economic growth that actually benefits the poor. There are other factors that influence this beyond inequality, corruption, and share of people living below certain poverty thresholds, as considered in this work. In some cases, especially for larger countries, different sub-regions might display considerable differences in how much of the VA is directed to the poor, making the use of country-level parameters like those in Eq. 4 less relevant. Certain countries have partly independent sub-regions, which might influence corruption, equality, or poverty. Further research should be dedicated to investigating the inclusion of additional factors in the S-LCIA method proposed, as well as opportunities for more sub-region-specific parameters.

Another factor might be that the VA generated in certain sectors could contribute differently to poverty reduction. Loayza and Raddatz (2010) write that labor-intensive sectors, such as agriculture, contribute more to poverty reduction than sectors requiring fewer laborers, such as mining. Similarly, Pegg (2006) propose that economic growth from extractive industries, like mining, generally reduce poverty to a lower degree. This is because infrastructure built for mining is often only useful for mining operations, downstream industries might not be present in the same region, and countries with much natural resources often have higher corruption. This might be a reason for the observed low contribution to social welfare from the cobalt mining in the DRC (Kara 2023). However, the universality of these relationships is uncertain. The artisanal mining of cobalt in the DRC is an example of a very labor-intensive mining sector, so from that perspective, it should have led to much poverty reduction in the DRC. Also, some countries have managed to benefit from extractive industries, so it is clearly possible to gain from economic growth due to mining.

Regarding the measurement of poverty, an alternative approach to considering the share people below poverty thresholds (P in Eq. 4) could have been to use the multidimensional poverty index (MPI) (United Nations Development Programme 2023). The MPI quantifies poverty in terms of three dimensions (health, education, and living standards) that together contains ten indicators. These indicators are weighted so that each dimension gets the same weight. However, several indicators get the value zero for many higher-income countries, including most European countries, and many countries are excluded due to lack of data. This makes it difficult to apply the MPI for a wide range of countries. It is furthermore not clear if the MPI is approximately linear, i.e., if MPI = 0.4 means roughly twice the poverty of MPI = 0.2.

Another area for further investigation might be the geographical resolution of the developed S-LCIA method. While the VA should be the same regardless of how many steps along the life cycle it is divided into, its disaggregation is restricted by where along the life cycle economic transactions take place. As shown in Fig. 3, there are in principle several such transaction points within the DRC, which in theory would enable a more detailed analysis of where in the DRC most of the VA is generated. However, it is unfortunately difficult to find transparent price data on, for example, the copper-cobalt ore sold to negociants, depot owners, and cobalt hydroxide refiners. Some data on this is reported by Kara (2023), but it was not deemed enough for quantitative social assessment purposes. Further data gathering might change this and allow for more detailed analyses.

It can finally be noted that corruption and inequality are in the developed S-LCIA method seen as factors that influence poverty reduction, specifically how much *VA* that benefits the poor. However, these factors are also listed as individual subcategories in the 2020 Guidelines for S-LCA, specifically as “corruption” and “wealth distribution,” respectively (UNEP 2020). When adopting an impact pathway approach, some subcategories can turn out to be causes, while others turn out to be effects. Another example of this can be seen in works about how income (related to subcategory “fair salary”) influences health (related to subcategory “health and safety”) (Arvidsson and Nordelöf 2025; Feschet et al. 2013). More research is needed to disentangle causes and effects among subcategories, which is important to avoid overlaps and redundancies in S-LCIA.

6 Conclusions

The proposed S-LCIA method quantifies the poverty reduction potential of products by considering the VA generated in processes and the share that benefits the poor. The share is estimated based on the corruption, inequality, and share of people living in poverty in the specific region. This method enables comparisons of poverty reduction potentials between product systems. It can also be used to identify poverty reduction hotspots, and it is possible to reveal whether they depend on high VA generation, low corruption, low inequality, or a high share of poverty. Such analyses can pinpoint improvement opportunities by different actors. The case study of cobalt supply indicated that the poverty reduction potential in the DRC is higher than in China and Finland. However, there may be local factors in the DRC that prevent the poverty reduction potential to become realized there, such as the strong presence of Chinese actors. Future development opportunities for the method include alternative ways to quantify the share of the VA that benefits the poor, and increasing the geographical resolution of the developed method.

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Anders Nordelöf: Conceptualization, methodology, investigation, data curation, writing—review and editing, funding acquisition.

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Data availability The data that supports the findings of this study is publicly available and cited in the article.

Declarations

Conflict of interest The authors declare no competing interests.

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