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Life cycle impacts assessment of two gold extraction systems in Colombia: open-pit and alluvial mining

Natalia A. Cano-Londoño[1,5] · Rafael Silva Capaz[2] · Christian Hasenstab[1] · Héctor I. Velásquez[1] · Neil McIntyre[3] · Glen D. Corder[3] · John A. Posada[4]

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Abstract

Purpose Gold mining has historically and significantly contributed to the Colombian economy. Gold extraction in Colombia is mainly done through two techniques: open-pit and alluvial mining. In this study, the environmental impacts of both these mining systems were analyzed using the life cycle assessment (LCA) framework, including identification of the system components that contribute most to impacts.

Methods Inventory data were obtained for two medium-scale mines in Colombia, one representing the open-pit method and the other the alluvial method. Environmental impacts were classified and characterized by mid-point impact categories and further aggregated into end-point indicators through the ReCiPe (v. 1.11) methodology, which uses a hierarchist perspective.

Results Results for end-point indicators show that the open-pit mining presents higher values in the human health damage category, influenced primarily by tailings and by the excavation process. For the alluvial mining, the overall impacts were an order of magnitude lower, with ecosystem quality as the most significant contributor due to the stripping of soil and vegetation. In the case of mid-point indicators, freshwater and marine ecotoxicity contribute the most to open-pit mining, while for alluvial mining, metal depletion and natural land transformation contribute the most. Climate change is also a significant impact category for alluvial and open-pit mining.

Conclusions The is a substantial difference in environmental impacts between the two mining systems: the quantified total environmental impact was 1.0×10^{04} points for the open-pit mine and 2.4×10^{03} points for the alluvial mine. Since these mines represent specific Colombian operational conditions, this conclusion cannot be confidently extended to other operational contexts. For example, results in other cases may depend on the local geological features and natural environment conditions. Knowing the critical mining supply chain stages for environmental performance will allow the decision-makers to provide the tools for more sustainable extraction and production.

Keywords Gold extraction · Life cycle assessment · Open-pit mining · Alluvial mining · Mining in Colombia

1 Introduction

There has been increasing public attention and scientific interest in the sustainability of mining practices and mining's contribution to welfare, economic development, social development, and environmental protection (Capaz et al. 2021; Tost et al. 2018; Tsalidis et al. 2022). Mining companies are expected to balance revenue considerations with those of sustainable regional development and environmental and social protection (Vintró et al. 2014).

Mining and processing of ores have environmental impacts on air, water, and soil (Vintró et al. 2014). Mineral grades (mass fraction of the ore that is the target metal) have been falling globally for some time (Domínguez et al. 2013). Gold production, in particular, has reached its "Hubbert peak" (Calvo et al. 2017) meaning that its production is declining as fast as it ever grew. There are still huge amounts of gold in the Earth's crust and oceans; however, lower grades require more ore to produce a unit of gold. Therefore, it is reasonable to suppose that the environmental impacts caused by gold mining processes—particularly related to energy consumption and generation of wastes—will become more significant

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✉ Natalia A. Cano-Londoño
nacanol@unal.edu.co;
NataliaAndrea.CanoLondono@UGent.be

Extended author information available on the last page of the article

in the future (Norgate and Haque 2010). In this context, the gold mining sector should seek opportunities to improve its environmental performance, prioritizing the production stages most critical to overall impacts (Awuah-offei 2016; Norgate and Haque 2010).

Life cycle assessment (LCA) is a well-established methodology to quantify environmental impacts across the productive supply chain of a product or service. Environmental impacts are caused by both the use of the natural resources (renewable and non-renewable) and by the emissions or waste released to the environment affecting ecosystems, natural resources, and human health (Londoño and Cabezas 2021) (Azapagic and Clift 1999). Using the LCA approach, the environmental burden associated with gold production stages (raw materials, manufacturing, and disposal) can be quantified and evaluated (Blengini et al. 2012). After that, strategies such as efficient raw material use, optimization technology, and residual flows valorization (waste reuse) can be implemented (Cano Londoño et al. 2019; Cano et al. 2020). Lesage et al. (2008) explored how to measure the impacts generated by mining activity using LCA and identified production chain hotspots that contributed most to the impacts. Other studies have applied LCA to the production of different minerals such as copper and aluminum (Spitzley and Tolle 2004), gold (Awuah-offei 2009; Chen et al. 2018; Kahhat et al. 2019; Norgate and Haque 2012), coal (Ditsele and Awuah-Offei 2012), bauxite (Bovea et al. 2007; Durucan et al. 2006), copper, nickel, and zinc (Douni et al. 2003; Northey et al. 2016; Suppen et al. 2006), and also for metal extraction (Norgate and Haque 2010). In the more recent cited examples, the applicability of LCA has become more advanced, with more specific consideration of elements of the mining life cycle (Burchart-Korol et al. 2016). Despite this, there are still methodological challenges associated with LCA, mainly with respect to the definition of functional units, scope of the analysis, and the selection of environmental impact categories. The lack of detailed information due to confidentiality requirements is also an obstacle to comprehensive assessment (Durucan et al. 2006).

Gold mining is generally undertaken either using alluvial mining, where gold is mined from the alluvial deposits of the flood plain, or larger scale mining, where ore is blasted out of rock either from an open-pit or underground void. The impacts of the less conventional alluvial technique are scarcely explored in the literature. The most significant studies are by Kahhat et al. (2019) and Valdivia et al. (2011) for informal mining in areas of the Peruvian Amazon rainforest, where mercury emissions and deforestation were seen as critical aspects. However, to date there are no published applications of LCAs to commercial scale or formalized alluvial gold mining, such as the case study in this paper. Valdivia and Ugaya (2011) estimated environmental indicators of artisanal and small-scale gold mining (alluvial and underground). The environmental impacts of medium to large-scale mining are often better regulated and managed, hence preventing the use of mercury and other toxic substances and resulting in different impacts and priority hotspots.

On the other hand, Chen et al. (2018) used LCA to assess environmental impacts of gold production in China, showing that metal depletion was the major contributor to the total environmental impact, dominated by the process of ore mining, followed by climate change, terrestrial acidification, human toxicity, and particulate matter formation.

Norgate and Haque (2012) concluded from using LCA that the mining and comminution stages contribute the most to greenhouse gas emissions, but their research did not consider other environmental impact categories. The two above-mentioned LCA studies on gold production, comprise only a few environmental categories, including loss of ecosystem quality, abiotic resources depletion, and climate change (Ferreira and Leite 2015), and do not explicitly include impact categories such as natural land occupation and transformation, freshwater ecotoxicity, and human ecotoxicity.

In the context of our current limited knowledge about the impacts of gold production over its life cycle, this paper aims to evaluate and compare the environmental performance of two medium-scale[1] mining organizations; open-pit and alluvial gold mining located in Colombia. It is worth noting that both are legally constituted entities (not considered as informal ones). In addition, this paper aims to highlight the stages of both open-pit and alluvial mining that are most critical for environmental performance and indicate process improvements that could provide more sustainable extraction and production.

2 Methodology

The LCA was carried out considering the following steps, as recommended by ISO 14040 (2006) (Environmental Management-Life Cycle Assessment-Principles and Framework. International Organisation for Standardisation, Geneva, Switzerland, 2006).

2.1 Goal and scope

As this study focuses on the environmental impacts analysis based on environmentally relevant physical flows, an attributional LCA was performed to estimate what share of the global environmental burden belongs to a product. This

[1] The Colombian mining classification lies on small, medium, and big scale based on the number of hectares granted in the mining concession: small (≤150 ha), medium (≥150 ha, ≤5000 ha), big (≥ 5000 ha, ≤10000) or according with the volume of the maximum annual mining production small (≤250000 m3/year), medium (≥250000 m3/year, ≤1300000 m3/year), big (1300000≥m3/year), and not on the number of workers (Código de Minas, Ley 685 DE 2001, 2001).

is contrary to a consequential LCA that estimates how the global environmental burdens are affected by the production and use of the product (Ekvall 2019). *Cradle-to-gate* boundaries were selected; in other words, the analysis includes the gold production process starting from raw material acquisition to the point of sale of the gold in ingots. The analysis addresses, for both mining systems, raw material acquisition, prospecting operations (vegetation and soil stripped), mineral extraction, ore beneficiation, metallurgical extraction, casting and molding, and waste treatment phases (Fig. 1). On-site transportation was included within the boundary of the analyzed systems, but off-site transport was not. To keep the scope manageable, the environmental burdens related to production and assembling of machinery and processing equipment, as well as building construction, were not included since their environmental impacts are distributed over their lifetime, and a relatively small contribution to the overall results would be expected (Cano Londoño et al.

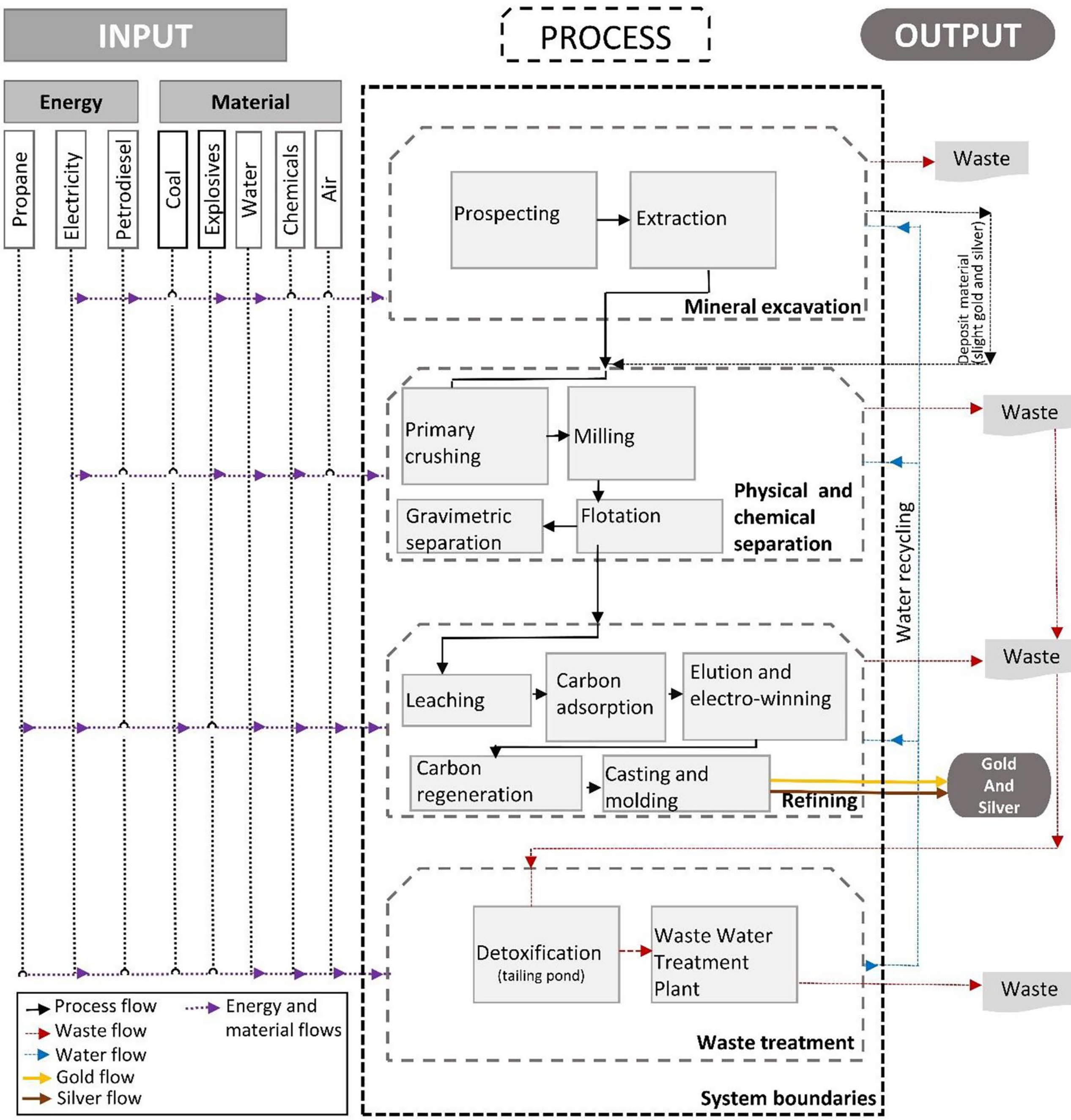

Fig. 1 Flow diagram of open-pit mining process from stripping to casting and molding

2019). For this study, the selected functional unit (FU) was 1.0 kg of gold with a millesimal fineness of 900. Silver and iron were considered as co-products from the open-pit and alluvial mining, respectively.

The environmental analysis was carried out with support of the Umberto NXT software (v. 7.1.10) (Ifu hamburg 2015) by using the ReCiPe (v. 1.11) methodology (Huijbregts et al. 2016) (see Section 2.3 for more details). The environmental impacts were partitioned between the different products based on the economic allocation, as a consistent approach for cause-oriented analyses, such as attributional studies (JCR 2010; UNEP-SETAP 2011; Weidema and Wesnæs 1996). Then the economic allocation was applied according to the Colombian market values for gold and silver. Average selling prices for 2018 were used (€36.21/g_{gold} and €0.50/g_{silver}) (Colombia Republic Bank 2017). For iron ore, the selling price of 0.03€/kg was used (Index Mundi 2016). The waste material that is stocked for posterior recovery of gold and silver was assumed to have a value according to its gold and silver content. It is worth noting that both are legally constituted entities (not considered as informal ones).

Regarding the use of the toxic substances in the gold concentration process, research has shown that around 90% of mercury (Hg) is recovered and that no recovered mercury is emitted to the environment or inhaled by the workers (Valdivia and Ugaya 2011). The Mercury International Treaty (UNEP, 2009) has supported local and national policy-making processes for the management of Hg (Valdivia and Ugaya 2011). Colombian mining legislation has prohibited the use of Hg from 2018 onwards (Law 1658 de 2013 2013), and no evidence has been found on the use of this chemical in these both mining processes (Cano 2018).

2.2 Life cycle inventory

2.2.1 The open-pit mining process

The ore extraction process uses conventional drilling, blasting, loading, and hauling, including excavation with hydraulic shovels. Before these stages, vegetation and soil are stripped (within the prospecting and extraction stages), and soil is stored for land restoration as illustrated in Fig. 1. Ore extraction, screening (sorting according to size), and grinding (crushing) of milled ore are followed by flotation, where foaming and organic agents are added to promote the flotation of the gold-containing sulfidic minerals and the confinement of other minerals. Fine materials (the overflow stream) are sent to the leaching circuit where sodium cyanide is added to dissolve the gold. Coarse materials (the underflow stream from the flotation unit) feed the milling and gravity concentration circuits. The gravity concentrate is sent to the leaching reactor, from which two streams are obtained: (i) combined gold and silver and (ii) waste tailings. The pulp from the leaching feeds the carbon-in-pulp (CIP) circuit (carbon adsorption), wherein the gold and silver are adsorbed onto activated carbon. Once the activated carbon has reached the required gold and silver content, it goes to the CIP elution circuit. The resulting elution mix is sent to the electro-winning process to selectively precipitate gold and silver which is sent to the casting furnace. Industrial wastewater is composed of flotation tailings (96.5%), leaching tailings, and CIP wastes (3.5%), which prior to disposal in the tailings pond are treated using hydrogen peroxide.

2.2.2 The alluvial mining process

Gold is mined from the alluvial deposits of the flood plain. Alluvial deposits are usually predominant in the lower part of a river's course, forming floodplains and deltas; however, they might be formed at any point where the river overflows its banks or where the flow is dammed or otherwise obstructed. Prior to extraction, the field is stripped of vegetation which is stored for later use in land restoration. The extraction process requires the use of suction dredgers, to remove superficial sands, clays, and silts, which are deposited in previously mined areas according to the cut and fill method as illustrated in Fig. 2. A dipper dredger is used along the suction dredger to remove deeper gravels and sands. Ore separation uses gravimetric concentration on board the dipper dredger, based on the high specific gravity of gold compared to barren rock. The material with lower specific gravity, containing the remaining gold, is passed to flotation. This method involves the use of foamers to promote flotation of the particles that are high in gold content. The recovered gold is directly sent to a drying step. As well as gold, ferrous minerals are separated as byproducts. The gold in the concentrated flow is melted in a tilting diesel melting furnace (see in Fig. 2 as casting and molding). Wastes from the separation process are passed through the sedimentation plant (wastewater treatment plant), whose aim is to recirculate 99% of the wastewater into the process with a quality suitable for that. Dewatered tailings are disposed of again in the tailings pond.

2.2.3 Inventory and background databases

Data availability and confidentiality can be obstacles for conducting LCA in some industrial sectors including mining (Toniolo et al. 2021; Valdivia et al. 2021). One of the accomplishments of this research is the fact that the material and energy flows of the two mining techniques (see Figs. 1 and 2) are inventoried through primary data provided by two mining companies. One company applying the open-pit mining method provided data based on planned operations for an 11-year period (2014–2025), while the other company using the alluvial mining method provided operational data for

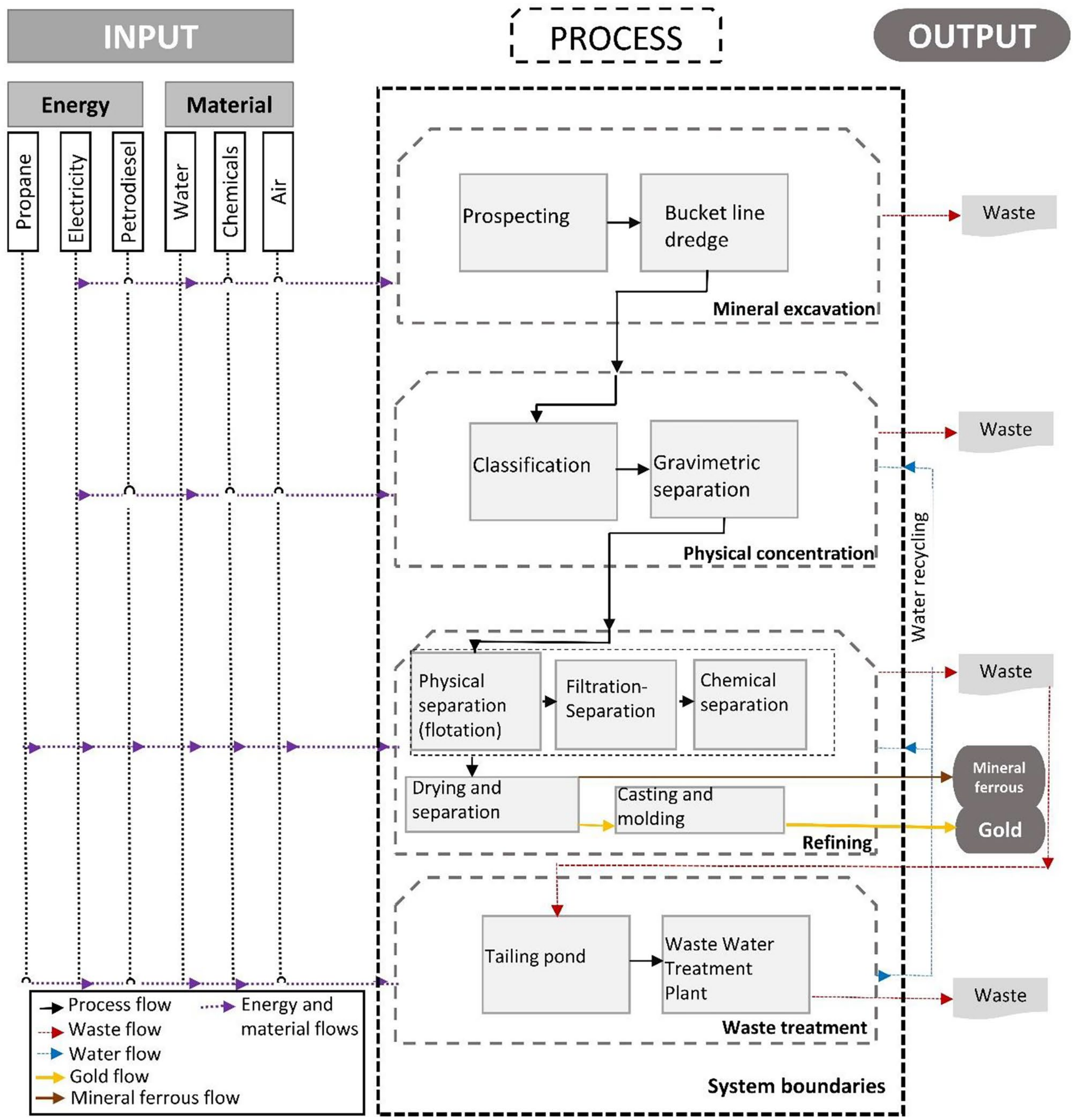

Fig. 2 Flow diagram of alluvial mining process from stripping to casting and molding

6 years (2012–2018) based on the mine's inventories. While the details of extraction techniques vary between mines, the selected mines are broadly representative of medium-scale mining practices in Colombia (Erkayaoğlu and Demirel 2016).

Table 1 shows the overall inputs and outputs for the two systems. Assuming that no losses occur in the processes of casting and molding, 19 t of gold per year and 21 t of silver per year are produced by the open-pit mining, which correspond to approximately 952 gold and 1077 silver ingots. In the alluvial mine, 3 t of gold per year are melted, which is approximately 155 ingots, and approximately 1.0 t per year of ferrous mineral result as a co-product. The inventory data are shown in more detail in Cano (2018) and Cano et al. (2019).

The secondary data for the background processes were taken from the Ecoinvent 3.1 database (Swiss Centre of Life Cycle Inventories 2014). Furthermore, to complete the life cycle inventory, the following data were used, and assumptions made:

Table 1 Life cycle inventories: material and energy input and outputs for open-pit and alluvial mining techniques

Gold mining techniques	Alluvial	Open-pit	Unit	Emissions released to:
Input				
Water	[a]9.79×10^{07}	[l]5.70×10^{07}	ton/year	
Energy (electricity)	[b]2.53×10^{11}	[m]2.03×10^{12}	kJ/year	
Energy (natural gas)	[c]1.60×10^{07}	[n]1.68×10^{10}	kJ/year	
Energy (petrodiesel)	[d]1.12×10^{09}	[o]1.15×10^{12}	kJ/year	
Oxygen (air from cylinders)	[e]40	[p]3.75×10^{05}	ton/year	
Others (services/chemicals)	[*]318.8	[**]1.01×10^{06}	ton/year	
Output				
Inert material removed (sterile mineral)	[f]1.06×10^{08}	[q]6.94×10^{07}	ton/year	Soil
Vegetation cover (clearing and stripping)	[g]60	[r]1.33×10^{03}	ton/year	Soil
Sludge tails (wet weight)	[h]4.52×10^{03}	[s]2.42×10^{07}	ton/year	Tailing pond (stored)
Energy losses	[i]4.74×10^{10}	[t]1.24×10^{12}	kJ/year	Air
Emissions of substances to air by combustion, detonation, trituration, leakage, etc	---	[u]2.204×10^{3}		---
Stored material with mineral of interest	---	[v]3.98×10^{07}	ton/year	Soil
Metal ferrous co-product (dry weight, 55% iron)	1.55	---	ton/year	
Silver co-product (dry weight)	---	[w]21.55	ton/year	
Gold (dry weight)	[j]3.10	[x]19.05	ton/year	
Recycling				
Water	[k]4.42×10^{05}	[y]4.79×10^{07}	ton/year	

--- data not considered in this study. Both mining are legally constituted entities (not considered as informal ones)

[*]Others in alluvial mining technology (ton/year): (1) services (7.3 organic material in domestic wastewater). (2) Chemicals: chemical separation (emulsifying agent 0.1; foaming agent 0.23; flotation agent 0.48), WTTP (coagulating agent 0.45), casting and molding (sodium borate 232.68 as a fluxing agent; calcium carbonate 77.56)

[**]Others in open-pit mining technology (ton/year): (1) chemicals: mineral excavation (1.41×10^{04} ammonium nitrate-fuel oil ANFO, 95% ammonium nitrate and 5% kerosene), chemical separation (1.08×1001 NaOH; 8.99×1001 NaCN), floatation (potassium ammonium xanthate 5.29×10^{02}; 4.37×10^{02} flotation agent), leaching (1.87×1003 NaCN, 2.19×10^{03} CaO), carbon adsorption (2.67×10^{03} activated carbon), detoxification (1.5×10^{02} CaO; 1.10×10^{00} H2O2; 1.27×10^{02} Na2S2O5), tailings pond (flocculating agent 3.11×10^{02}), elution and carbon regeneration (9.91×10^{05} inorganic chemicals)

[a]Water in alluvial mining technology (ton/year): exploration (1.25×10^{02}), clearing and stripping (1.15×10^{06}), float up of suction dredger (1.00×10^{07}), mechanical screening (7.46×10^{07}), hydraulic jigs (1.12×10^{07}), sluice boxes (4.84×10^{05}), physical separation (4.46×10^{05}), waste tailing treatment plant ($3.80\times^{-01}$), services (9.38×10^{03} water for domestic use, not used into operational process)

[b]Electrical energy in alluvial mining technology (kJ/year): clearing and stripping (9.98×10^{10}), dipper dredger (6.86×10^{10}), mechanical screening (4.47×10^{10}), hydraulic jigs (2.33×10^{10}), sluice boxes (2.76×10^{09}), physical separation (1.92×1008), filtration-separation (7.67×10^{07}), chemical separation (1.15×10^{08}), waste tailing treatment plant (WTTP) (4.77×1007), tailings pond (6.95×10^{07}), services (1.35×10^{10} to support suction dredger, dipper dredger, and administrative offices). Hydropower run-of-river electricity production supplies 100% of the energy demand from alluvial mining

[c]Gas energy (propane) in alluvial mining technology (kJ/year): drying and separation of ferrous minerals (1.60×10^{07})

[d]Diesel fuel (derived from petroleum) in alluvial mining technology (kJ/year): exploration (2.86×10^{08}), casting and molding (4.33×10^{06}), services (8.34×10^{08} to support suction dredger, dipper dredger)

[e]Oxygen (air) in alluvial mining technology (ton/year): drying and separation (20), tailings pond (20)

[f]Inert material removed (sterile mineral in dry weight) in alluvial mining technology (ton/year): reserves evaluation, exploration (5.61×10^{02}); reserves evaluation, clearing and stripping (3.65×10^{07}); mineral extraction, dipper dredger (6.95×10^{07})

[g]Vegetation covered harbors in alluvial mining technology (ton/year): clearing and stripping (60 corresponding to 140 hectares)

[h]Sludge tailings (wet weight) in alluvial mining technology 4.52×10^{03} with 98.7% humidity

[i]Energy losses in alluvial mining technology (kJ/year): clearing and stripping (9.98×10^{09}), dipper dredger (6.86×10^{09}), mechanical screening (2.41×10^{10}), hydraulic jigs (2.33×10^{09}), sluice boxes (7.73×10^{08}), physical separation (1.92×10^{07}), filtration-separation (2.15×10^{07}), chemical separation (3.22×10^{07}), WTTP (1.34×10^{07}), tailing pond (1.94×10^{07}), services (3.10×10^{09} to support suction dredger, dipper dredger, and administrative offices), drying and separation of ferrous minerals (1.60×10^{06}), exploration (1.80×10^{08}), casting and molding (1.99×10^{03}). Note: energy losses are calculated on equipment efficiency

[j]Gold (dry weight) in alluvial mining technology (ingot/year): 155 each 20 kg

[k]Recycling in alluvial mining technology, water treated from WTTP to physical separation

[l]Water consumption in open-pit mining technology (ton/year): clearing and stripping (5.65×10^{06} water for irrigation to minimize total sus-

Table 1 (continued)

pended particles in the air), mineral excavation (5.08×10^{06} spray irrigation systems to minimize total suspended particles in the air), secondary milling (3.59×10^{07}), gravimetric separation (8.32×10^{06}), floatation (2.08×10^{06}), elution (6.96×10^{05}). Primary crushing step is not significant in spray irrigation systems and is not quantified

[m]Electrical energy in open-pit mining technology (kJ/year): mineral excavation (8.08×10^{10}), primary crushing (7.82×10^{10}), secondary milling (1.36×10^{12}), gravimetric separation (2.15×10^{09}), floatation (1.97×10^{11}), leaching (4.45×10^{10}), carbon adsorption (8.05×10^{09}), detoxification (2.02×10^{08}), tailings pond (5.34×10^{10}), elution and carbon regeneration (3.90×10^{10}), casting and electro-winning (7.99×10^{09}), other services such as administrative offices, public services (1.55×10^{11})

[n]Gas energy (liquefied petroleum gas) in open-pit mining technology (kJ/year): other services (1.68×10^{10})

[o]Diesel fuel (derived from petroleum) in open-pit mining technology (kJ/year): mineral excavation (1.14×10^{12}), casting and electro-winning (1.35×10^{09}), other services (5.35×10^{09} lightweight vehicles)

[p]Oxygen (air) in open-pit mining technology (ton/year): floatation (2.27×10^{04}), leaching (3.75×10^{05})

[q]Inert material removed (sterile mineral in dry weight) in open-pit mining technology (ton/year): reserves evaluation, clearing, and stripping (1.09×10^{03}); mineral excavation (6.93×10^{07})

[r]Vegetation covered harbors in open-pit mining technology (ton/year): clearing and stripping (1.33×1003 vegetation covered harbors)

[s]Sludge tailings (wet weight) in open-pit mining technology (ton/year): 2.42×10^{07} with 2.36×10^{-04}% humidity

[t]Energy losses open-pit mining technology (kJ/year): mineral excavation (7.48×10^{11}), primary crushing (1.49×10^{10}), secondary milling (2.59×10^{11}), gravimetric separation (2.15×10^{08}), floatation (5.50×10^{10}), leaching (4.45×10^{09}), carbon adsorption (3.62×10^{09}), detoxification (5.64×10^{07}), tailings pond (5.34×10^{09}), elution and carbon regeneration (1.09×10^{10}), casting and electro-winning (1.65×10^{09}), other services (1.39×10^{11} administrative offices, public services). Note: energy losses are calculated on equipment efficiency

[u]Emissions, total suspended particles in open-pit mining technology (ton/year): mineral excavation (1.75×10^{03}), primary crushing (2.41×10^{01}), secondary milling (7.09×10^{01}), tailings pond (3.75×10^{02})

[v]Stored material with mineral of interest (ton/year): 55% of the extracted material (3.98×10^{07}) with a significant gold concentration is stored (3.98×10^{07}) for future beneficiation

[w]Silver (dry weight) in open-pit mining technology (ingot/year): average 1078 each 20 kg

[x]Gold (dry weight) in open-pit mining technology (ingot/year): average 952 each 20 kg

[y]Recycling in open-pit mining technology, water treated from WTTP to all the process

- In the open-pit mining, the area occupied by the extraction activity increased by 9.48 hectares/year. Service areas (storage warehouse, hydraulic and mechanical workshop, mineral beneficiation plant, administrative office, heavy machinery workshop) occupy 3.45 hectares and the tailings pond 15.65 hectares (data provided by the open-pit mine company).
- In the alluvial mining, the area occupied by the extraction activity is equal to 140 hectares/year. Service areas (storage warehouse, hydraulic and mechanical workshop, mineral beneficiation plant, administrative office, heavy machinery workshop) occupy 3.5 hectares and the tailings pond 1 hectare (data provided by the alluvial mine company).
- Time needed for natural restoration of forest in both mine systems was set to 40 years (Chazdon et al. 2016). However, for land occupied by the tailings ponds, the recovery time was considered to be 130 years in both systems (Swiss Centre of Life Cycle Inventories 2014).
- For the open-pit mining, the company reports that approximately 70 substances are present in the tailings. For alluvial mining, only 17 substances were reported, with several limited by confidentiality issues.
- The electricity source mix has been fixed to Colombia's national mix during 2012–2020, which is hydropower (70.4%), natural gas (15.2%), coal (8.4%), wind (0.1%), biomass (0.7%), fuel oil (0.6%), Jet-A1 mix fuel (1.78%), fuel engine oil (2.7%), Jet-A1 (0.04%), and other renewable sources (0.09%) (Ministerio de Minas y Energía, 2021).
- For the open-pit mining, the energy demands of refining gold and silver were assumed as 325 kWh/ton gold and 630 kWh/ton, respectively, following Norgate & Haque (2012).
- There have been no leakages of organic and inorganic chemicals (all chemicals are contained in the tailings pond), according to data provided by the mining companies.
- In the long term (100 years), all chemical substances within the sulfidic tailings are liberated into the environment, ultimately reaching groundwater. No chemical reactions in the tailings have been considered.
- All chemicals used in both mining processes are taken as generic chemicals split into organic and inorganic chemicals based on the Ecoinvent 3.1 database (Swiss Centre of Life Cycle Inventories 2014). Exceptions are sodium cyanide (NaCN), calcium oxide (CaO), sodium borate, and activated carbon, which are explicitly considered from foreground system for the open-pit mining process.

2.3 Environmental impacts quantification

The environmental impacts were quantified by *mid-point* impact categories and aggregated by *end-point* indicators assigned through ReCiPe methodology (hierarchist, including long-term effects) (Huijbregts et al. 2016). Figure 3 presents the categories considered here for both types of indicators.

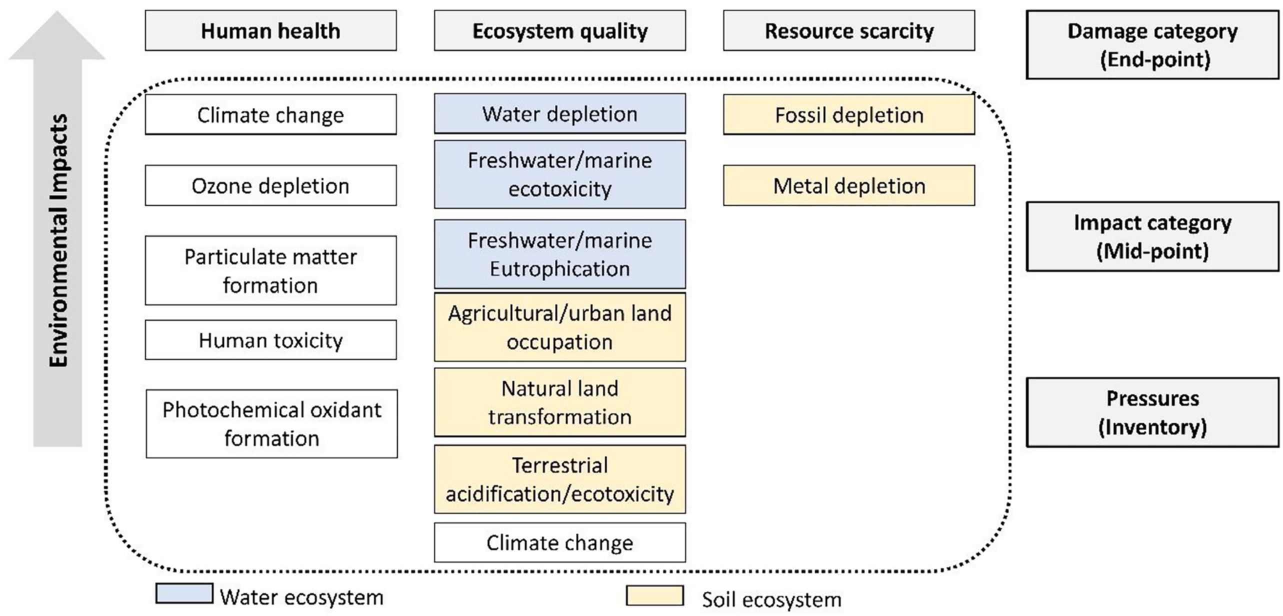

Fig. 3 Environmental impacts categories considered here according to ReCiPe method

The mid-point indicators were obtained from the characterization factors applied to the in–out environmental flows of the system-process (Eq. 1). Each factor indicates the environmental impact per unit of stressor (e.g., per kg of resource used or emission released).

$$IC = \sum_{s} (CF_{(s)} * EI_{(s)}) \tag{1}$$

where IC is the mid-point indicator, $CF_{(s)}$ is the characterization factor of each resource or emission s, and $EI_{(s)}$ is the resource or emission inventory.

To better explore the relative magnitude of the impact categories, the mid-point results were normalized according to the reference values suggested by ReCiPe (v. 1.11).

Finally, the mid-point results were aggregated to end-point indicators, also known as damage categories, which, according to the ReCiPe method, comprise three different areas: human health, ecosystem quality, and resource scarcity (Jolliet and Müller-wenk 2004) (see Fig. 3). The aggregation used the weighting factor method:

$$DC = \sum_{i}^{N} WF_{(i)} * IC_{(i)} \tag{2}$$

where DC is the value of a damage category or end-point indicator, $WF_{(i)}$ is the weighting factor for mid-point indicator i, $IC_{(i)}$ is the normalized mid-point indicator i, and N is the number of mid-point indicators relevant to the damage category being calculated. The human health category refers to potential effects, which only become relevant if people are exposed. The potential effects assume emissions of a period of 100 years, and eventually the emitted contaminants will affect humans.

3 Results and discussion

3.1 Environmental analysis according to the mid-point indicators

Table 2 shows the mid-point impact categories for the open-pit and the alluvial mining. Other inventories reported in Ecoinvent 3.1—Peru, Papua New Guinea, and Rest of the World—were also analyzed for comparison purposes. It is worth highlighting that all the inventories sourced from Ecoinvent 3.1 are based on the open-pit mining technique. Environmental impacts were economically allocated to the main product in both mining systems as indicated in Section 2.1 (Fig. 4). In the alluvial mining, nearly 100% of the environmental impacts are attributed to gold. This is due to the low price and level of production of iron compared to gold. In turn, the majority of impacts correspond to mining of the gold ore (69.70%), followed by the deposited material (29.22%). As this material has low economic value, it is stored for posterior beneficiation. Furthermore as it presents low concentrations of gold and silver (Au, 5.0×10^{-05}%, and Ag, 8.1×10^{-05}%), it results in a small allocation of impacts to silver production (1.08%).

According to Fig. 5, the two mining processes are dissimilar over all the impact categories. In general, alluvial mining presents the lowest impact. The open-pit mining has lower values for only agricultural land occupation, water

Table 2 Comparison of gold mining processes according to mid-point impact categories

Impact categories aggregated	Impact categories	Alluvial mining technology		Open-pit mining technology		Ecoinvent 3.1. database Peru		Ecoinvent 3.1. database Papua New Guinea		Ecoinvent 3.1. database Rest of the World	
		Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)
Ecosystem (soil)	Agricultural land occupation, (m^2a)	1.81×10^{04}	3.33×10^{00}	2.65×10^{02}	4.88×10^{-02}	4.13×10^{02}	7.61×10^{-02}	1.24×10^{03}	2.29×10^{-01}	6.06×10^{02}	1.12×10^{-01}
	Natural land transformation, (m^2)	4.64×10^{02}	3.86×10^{01}	1.93×10^{01}	1.60×10^{00}	5.17×10^{00}	4.29×10^{01}	9.45×10^{00}	7.86×10^{-01}	6.60×10^{00}	5.49×10^{-01}
	Urban land occupation, (m^2a)	4.21×10^{02}	5.43×10^{-01}	1.30×10^{03}	1.68×10^{00}	1.09×10^{03}	1.41×10^{00}	1.20×10^{03}	1.55×10^{00}	1.09×10^{03}	1.40×10^{00}
	Terrestrial acidification, (kg SO_2 eq)	8.05×10^{-01}	2.11×10^{-02}	2.07×10^{02}	5.42×10^{00}	1.90×10^{02}	4.98×10^{00}	2.54×10^{02}	6.66×10^{00}	2.41×10^{02}	6.31×10^{00}
	Terrestrial ecotoxicity, (kg 1,4-DB eq)	1.15×10^{-02}	1.94×10^{-03}	1.03×10^{01}	1.74×10^{00}	2.20×10^{00}	3.72×10^{-01}	1.95×10^{00}	3.28×10^{-01}	2.53×10^{00}	4.27×10^{-01}
Ecosystem (water)	Freshwater ecotoxicity (kg 1,4-DB eq)	1.29×10^{01}	3.01×10^{00}	7.39×10^{04}	1.72×10^{04}	1.41×10^{04}	3.28×10^{03}	6.33×10^{03}	1.47×10^{03}	1.24×10^{04}	2.89×10^{03}
	Freshwater eutrophication, (kg P-eq)	4.20×10^{-02}	1.45×10^{-01}	4.94×10^{02}	1.71×10^{03}	3.80×10^{02}	1.31×10^{03}	1.70×10^{02}	5.87×10^{02}	3.24×10^{02}	1.12×10^{03}
	Marine ecotoxicity (kg 1,4-DB eq)	1.14×10^{01}	4.63×10^{00}	2.11×10^{04}	8.57×10^{03}	1.25×10^{04}	5.08×10^{03}	9.07×10^{03}	3.68×10^{03}	1.18×10^{04}	4.79×10^{03}
	Marine eutrophication, (kg N-eq/m^3)	3.94×10^{-01}	5.37×10^{-02}	8.55×10^{01}	1.16×10^{01}	1.06×10^{02}	1.44×10^{01}	1.20×10^{02}	1.64×10^{01}	1.26×10^{02}	1.72×10^{01}
	Water depletion (m^3)[a]	2.82×10^{04}		4.91×10^{02}		1.89×10^{01}		1.23×10^{03}		1.34×10^{02}	
Resources	Fossil depletion, (kg oil eq)	4.29×10^{01}	3.32×10^{-02}	3.94×10^{03}	3.06×10^{00}	2.48×10^{03}	1.92×10^{00}	9.82×10^{03}	7.61×10^{00}	5.06×10^{03}	3.92×10^{00}
	Metal depletion (kg Fe-eq)	7.00×10^{04}	1.57×10^{02}	8.29×10^{04}	1.86×10^{02}	8.23×10^{04}	1.85×10^{02}	8.14×10^{04}	1.83×10^{02}	1.01×10^{05}	2.28×10^{02}
Human health	Climate change (kg CO_2 eq)	1.66×10^{02}	2.41×10^{-02}	1.51×10^{04}	2.19×10^{00}	8.07×10^{03}	1.17×10^{00}	2.90×10^{04}	4.22×10^{00}	1.57×10^{04}	2.28×10^{00}
	Ozone depletion, (kg CFC-11 eq)	1.63×10^{-05}	4.34×10^{-04}	1.06×10^{-03}	2.81×10^{-02}	1.07×10^{-03}	2.84×10^{-02}	3.46×10^{-03}	9.18×10^{-02}	2.04×10^{-03}	5.43×10^{-02}
	Particulate matter formation (kg PM10 eq)	6.91×10^{-01}	4.92×10^{-02}	1.65×10^{02}	1.18×10^{01}	6.56×10^{01}	4.67×10^{00}	1.04×10^{02}	7.41×10^{00}	8.44×10^{01}	6.00×10^{00}

Table 2 (continued)

Impact categories aggregated	**Impact categories**	**Alluvial mining technology**		**Open-pit mining technology**		**Ecoinvent 3.1. database Peru**		**Ecoinvent 3.1. database Papua New Guinea**		**Ecoinvent 3.1. database Rest of the World**	
		Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)	Non-normalized values (units/year)	Normalized values (units/year)
	Photochemical oxidant formation (kg NMVOC)	7.86×10^{-01}	1.38×10^{-02}	2.18×10^{02}	3.84×10^{00}	2.34×10^{02}	4.12×10^{00}	3.15×10^{02}	5.55×10^{00}	2.87×10^{02}	5.05×10^{00}
	Human toxicity (kg 1,4-DB eq)	7.35×10^{01}	2.25×10^{-01}	5.56×10^{05}	1.70×10^{03}	6.42×10^{05}	1.97×10^{03}	2.88×10^{05}	8.82×10^{02}	5.47×10^{05}	1.68×10^{03}

The results are expressed per 1.00 kggold

[a]ReCiPe (v. 1.11) does not include a normalization factor for water depletion

depletion, and natural land transformation. The differences in environmental performance between the two techniques are explained by the extractive methods, technologies implemented, mineral purity, and deposit conditions, which will be analyzed in the following sections.

Table 2 and Fig. 5 show that, for the open-pit mining, terrestrial acidification is most relevant to the ecosystem (soil) categories. The same conclusion is reached when considering the Ecoinvent 3.1 inventories. This is due to the toxic substances contained in sulfidic tailings and the large areas required for their deposition. For the alluvial mining, the natural and agricultural land transformations are more relevant due to the soil stripping (140 ha/year).

Results in Table 2 suggest that, for water-based categories, marine ecotoxicity is the most important impact of alluvial mining and open-pit mining according to the Ecoinvent databases for Peru, Papua New Guinea, and Rest of World. Furthermore, results from Ecoinvent databases process present that freshwater ecotoxicity is the critical environment impact but is lower than the case study reported in this study (Table 2). Regarding the human health-based categories, human toxicity and particulate matter formation categories present the most significant impacts for open-pit mining. Finally, in the resource-based categories, the metal depletion category has the highest impact as would be expected for a metal mining process (Kahhat et al. 2019).

The open-pit mine case study presents similar results to those sourced from the Ecoinvent database. Although all these are open-pit mining, the case study presents the highest values for most of the impact categories, as shown in Table 2, except for terrestrial ecotoxicity, marine eutrophication, human toxicity, climate change, and photochemical oxidant formation. The laboratory analysis of the open-pit mine tailings, undertaken by the mining company, shows that there are specific, potentially toxic chemical substances present. Analysis of specific chemicals is in contrast to generic LCI/LCA approaches that base their findings on aggregating chemicals. All potentially toxic chemicals were considered in the mass balance as well as in the life cycle inventory (for both input and output stream values), data modeling, and result interpretation. However, results for each chemical are not presented here due to a non-disclosure agreement. Almost 75% of freshwater ecotoxicity and 99% of eutrophication stem from the phosphorus content of tailings. The Barium content of tailings, which emanates from the extraction stage (soil elements), accounts for nearly 40% of human toxicity. In contrast, in the Ecoinvent dataset for Peru, Barium does not play an important role. This might be because elements naturally present in the soils have not been considered in the mining life cycle inventories used in the Ecoinvent dataset for Peru. Hence, it is relevant to include primary data as far as possible in the environmental evaluations because of the specificity of the local conditions (e.g.,

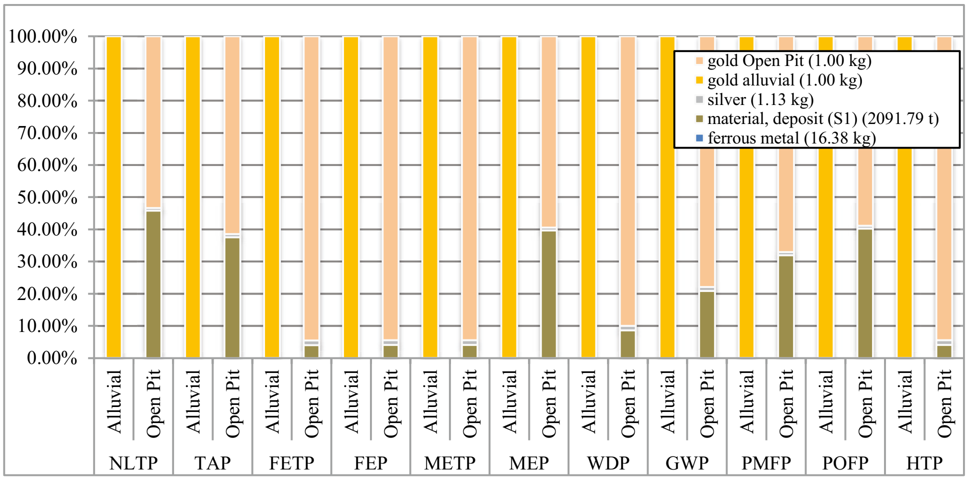

Fig. 4 Economic allocation for the Environmental impacts for products and co-products to both mining systems. NLTP natural land transformation, TAP terrestrial acidification, FETP freshwater ecotoxicity, FEP freshwater eutrophication, METP marine ecotoxicity, MEP marine eutrophication, GWP climate change, POFP photochemical oxidant formation, PMFP particulate matter formation, WDP water depletion, HTP human toxicity

geographical, geological, and extraction techniques, among others) that are not possible to be tackled by the Ecoinvent dataset. Impact values depend highly on the chemicals analyzed; therefore, as far as possible, all toxic chemicals to be potentially used should be accounted for in future works. The freshwater and marine ecotoxicity were the most affected impact categories for both mining techniques. The open-pit mine presents the highest impacts related to water-based categories, although the alluvial mine contributes significantly to water depletion due to intensive use of water. The total water consumed in the open-pit is equal to 2.99×10^{09} t/kg$_{gold}$ year and in the alluvial mine is 3.16×10^{10} t/kg$_{gold}$ year. In the alluvial mine, 42% of the water used returned to river basin, while in the open-pit mine, 49% is recirculated into the process.

Based on the normalized values, eleven indicators have been selected as relevant for the analysis (Figs. 6 and 7). Figure 6 shows the contribution of each stage of the open-pit process to the environmental impact categories. The tailings (as residual flow from flotation) and refining process followed by the mineral excavation (extraction) process were the most impactful activities in this study, together with the electricity consumed and the inorganic chemicals consumed.

Ninety-six percent of the tailings in open-pit mining come (see Fig. 1) from the refining phase, mainly the leaching process, which contributed the most to natural land transformation, freshwater ecotoxicity, human toxicity, marine ecotoxicity, and freshwater eutrophication. This is a consequence of the contaminants in the tailings. The extraction process had the next biggest impact due to particulate matter formation, photochemical oxidant formation, terrestrial acidification, and marine eutrophication resulting from the use of diesel, electricity, and explosives. Water depletion is mainly due to its use in the physical and chemical separation process. Climate change impact is mostly a result of the use of electricity generated using fossil fuels (99% of the total energy consumed).

In the case of the alluvial mining (see Fig. 2), the electricity demand, the stripping process, and the water extraction from the basin for the mineral excavation stage contributed the most to the impact categories analyzed, as presented in Fig. 7. Furthermore, the stripping process fully drives the natural land transformation.

The hydropower run-of-river electricity production supplies all the energy demand from alluvial mining and causes a large proportion of the impacts in all categories, except for natural land transformation and water depletion. As inventory data were taken from the Ecoinvent database as no data were provided by the mining company, it is possible that the local ecosystem features lead to greater or smaller hydropower impacts than those shown in Fig. 7.

Similar to the open-pit mining, water is depleted when extracting river water for use in the alluvial mining separation processes.

3.2 Environmental analysis according to the end-point indicators

The performance of each mining technology by end-point indicators is presented in this section. Table 3 shows that the total impact of open-pit mining (1.01×10^{04} pts) is approximately four times higher than that of alluvial mining with (2.38×10^{03} pts). The damage category with highest values in open-pit mining is human health (89.2%) and in alluvial mining is ecosystem quality (99.3%).

Over both mining methods, the largest estimated potential effects on human health, assuming current emissions continue over a period of 100 years, are due to the chemical elements in tailings (mainly manganese and Barium) and due to particulate matter generated in the open-pit excavation process (blasting process and other excavation activity). In alluvial mining, where the gold concentration uses physical methods instead of chemicals, there is less damage to human

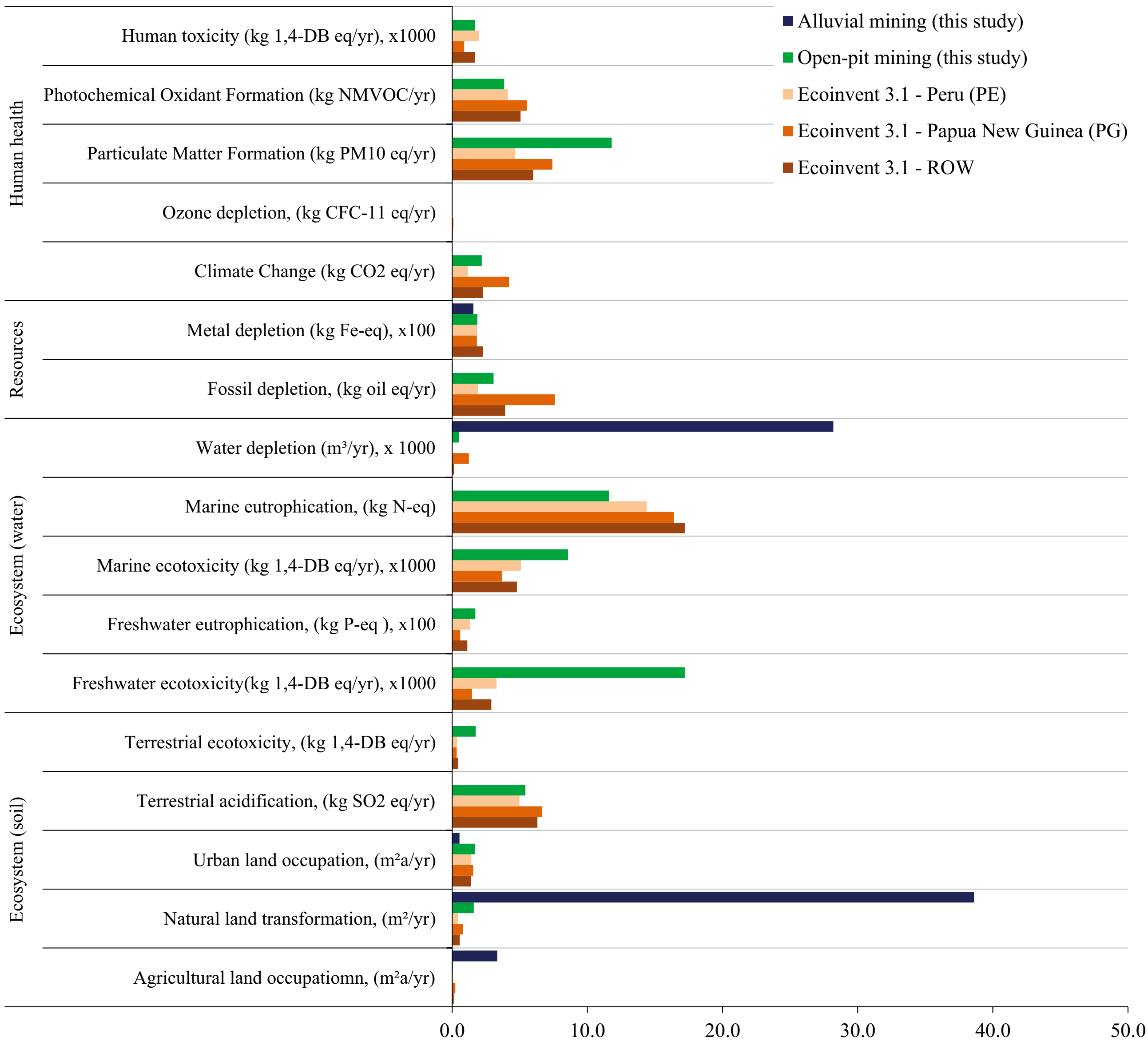

Fig. 5 Comparison of mid-point environmental impacts of different mining systems (normalized results, except for water depletion). ALOP agricultural land occupation, NLTP natural land transformation, ULOP urban land occupation, TAP terrestrial acidification, TETP terrestrial ecotoxicity, FETP freshwater ecotoxicity, FEP freshwater eutrophication, METP marine ecotoxicity, MEP marine eutrophication, FDP fossil depletion, MDP metal depletion, GWP climate change, ODP ozone depletion, POFP photochemical oxidant formation, PMFP particulate matter formation, WDP water depletion, HTP human toxicity

health but more damage to ecosystem quality due to the land use transformation of 140 hectares.

Despite the differences between alluvial and open-cut mining results, there is no simple answer to which one has less environmental impacts. For instance, the open-pit mining system impacts more on human health, whereas alluvial mining causes more damage to ecosystem quality. It is not possible to compare these and draw general conclusions for this activity. For instance, where a large local population is adjacent to an open-pit mine, human health damage category is likely to become a critical impact category than in areas with less population.

The contribution of each component of the open-pit mining process to damage indicators is illustrated in Fig. 8. Tailings and extraction are the most critical stages in open-pit mining. Tailings have impacts on human toxicity from the effects of manganese and Barium and natural land transformation due to tailings storage. These are followed in order of importance by electricity generation, the stripping process, and the storage of excavated material. Burning diesel for excavation operations is another source of human health impact.

In the open-pit mining, 39.8% of the ecosystem quality impact comes from the electricity process, followed by

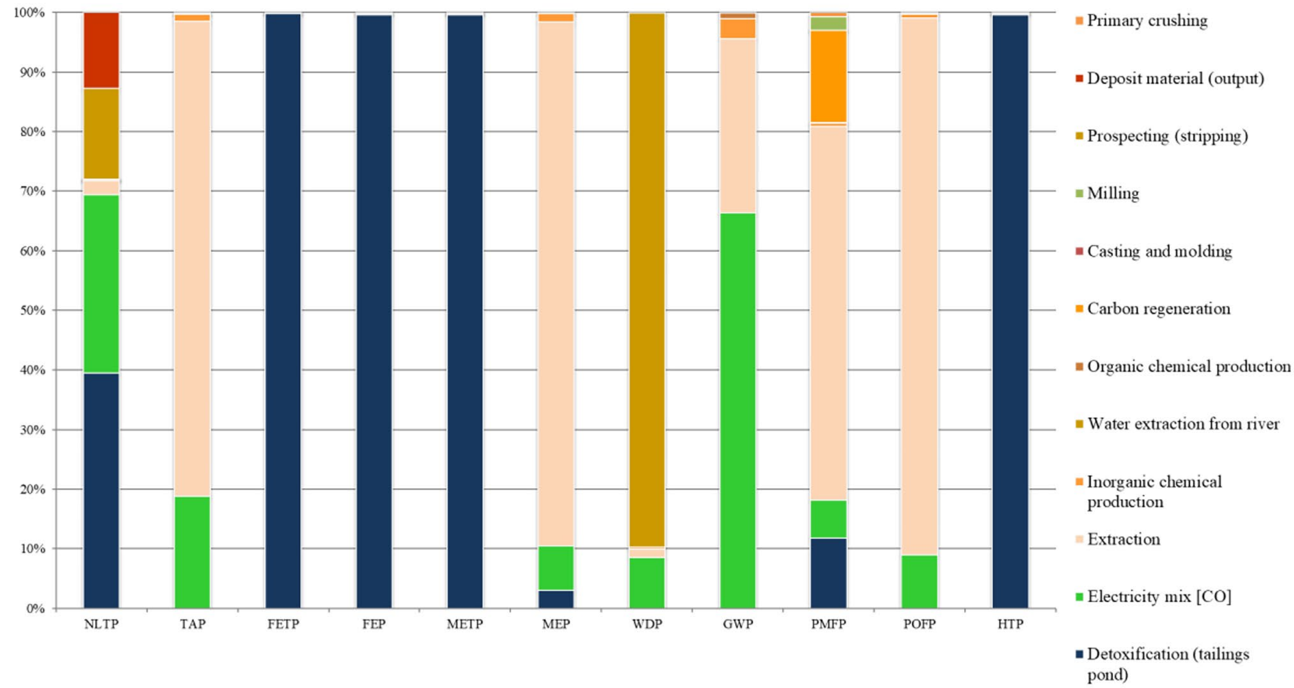

Fig. 6 Mid-point indicators for open-pit mining, according to the contribution of the main processes. NLTP natural land transformation, TAP terrestrial acidification, FETP freshwater ecotoxicity, FEP freshwater eutrophication, METP marine ecotoxicity, MEP marine eutrophication, GWP climate change, POFP photochemical oxidant formation, PMFP particulate matter formation, WDP water depletion, HTP human toxicity

tailings and the extraction process with contributions of the 38.4% and 13.9%, respectively. For the human health indicator, 87.0% of the total impact stems from the tailings process, followed by carbon regeneration, and electricity process, which contribute 7.4% and 3.3%, respectively. For the resource indicator, the electricity process has the greatest contribution of 42.0%, while diesel consumption and extraction contribute 25.5% and 21.2%, respectively.

For the case of the alluvial mining, 96.1% of the ecosystem quality damage is associated with the stripping process,

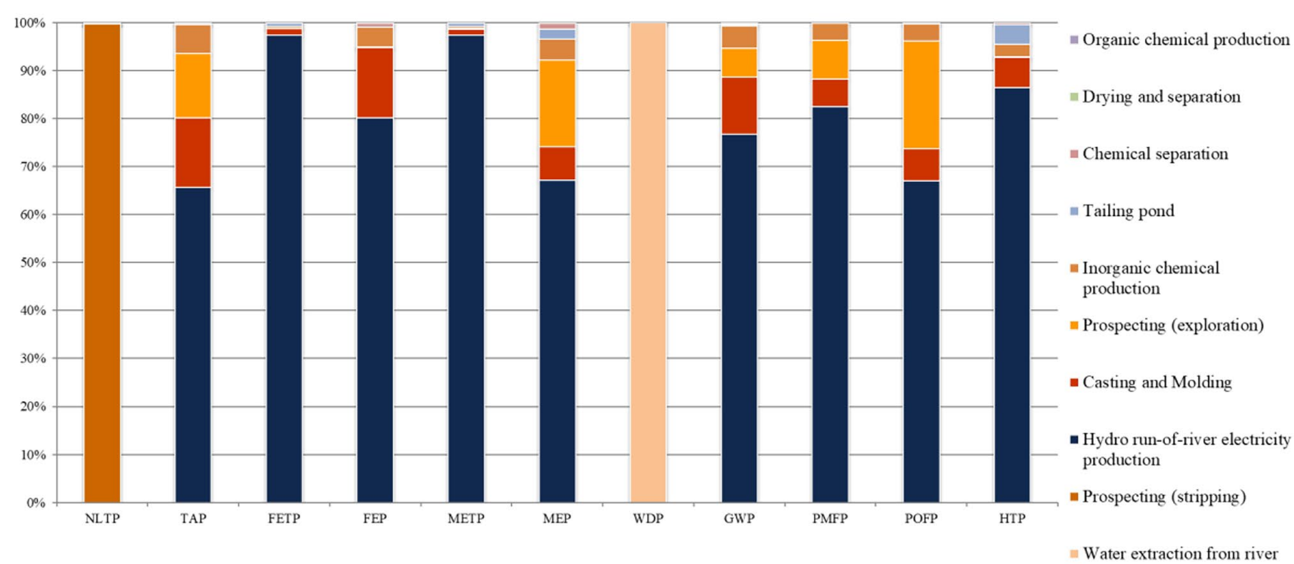

Fig. 7 Mid-point indicators for alluvial mining, according to the contribution of the main processes. NLTP natural land transformation, TAP terrestrial acidification, FETP freshwater ecotoxicity, FEP freshwater eutrophication, METP marine ecotoxicity, MEP marine eutrophication, GWP climate change, POFP photochemical oxidant formation, PMFP particulate matter formation, WDP water depletion, HTP human toxicity

Table 3 Environmental performance of open-pit and alluvial mining systems according to end-point indicators to the total environmental impacts in points

Indicator	Open-pit mining [points]	Alluvial mining [points]	Percentage open-pit mining [%]	Percentage alluvial mining [%]
Ecosystem quality [points]	6.02×10^{02}	2.37×10^{03}	6.0	99.3
Human health [points]	8.98×10^{03}	9.35×10^{00}	89.2	0.4
Resources [points]	4.88×10^{02}	7.43×10^{00}	4.8	0.3
Single indicator: total [points]	$\mathbf{1.01 \times 10^{04}}$	$\mathbf{2.38 \times 10^{03}}$	**100.00**	**100.00**

Total points values are already weighted in the previous aggregation step under hierarchist perspective (ecosystem weight: 400. Human health weight: 300. Resources weight: 300) ReCiPe (v. 1.11)

66.6% of resource use is associated with electricity production, and 71.3% of human health damage come from hydropower production run-of-river. For alluvial mining, Fig. 9 illustrates how the stripping stage is the most critical process in environmental terms, with natural land transformation and agricultural land occupation being the most relevant environmental impact categories. That is, 93.0% of the natural land transformation corresponds to the stripping process mainly due to the area occupied by extraction activity (140 hectares/year) under the assumption of recovery of the natural forest over 40 years (Chazdon et al. 2016).

Even though alluvial mining largely avoids the consumption of chemicals and energy in the separation process, it does result in land demand causing a large natural land transformation. On the other hand, the open-pit mining is primarily a dry process, involving significant amounts of particulate matter emissions through the mineral excavation stage as well as chemicals used in the separation process, which increase the potential exposure of humans to toxic substances.

LCA does have some limitations. For instance, from the results of the analysis reported here, it could be interpreted that the alluvial mining has much less impacts compared to open-pit mining. This early conclusion should be avoided as there might be some room for revision once primary data are available, while the inventory of the latter comprises approximately 70 substances present in the tailings stage, and the former was described by only 17 substances, due to confidentiality reasons as mentioned earlier. This could create a misunderstanding on the policy formulation for management of the possible environmental impacts (reduction, mitigation, and compensation) related to these chemical substances. Concerning other impact categories, the results may reasonably be comparable between the two mining methods.

Furthermore, the factors related to the interactions of contaminants with humans (e.g., type of population affected, level of risk, vulnerability, among others) have not been not fully considered. Subsequently, indicators such as human health should not be considered as an actual measure but as an indication of "potential damage." The fact that

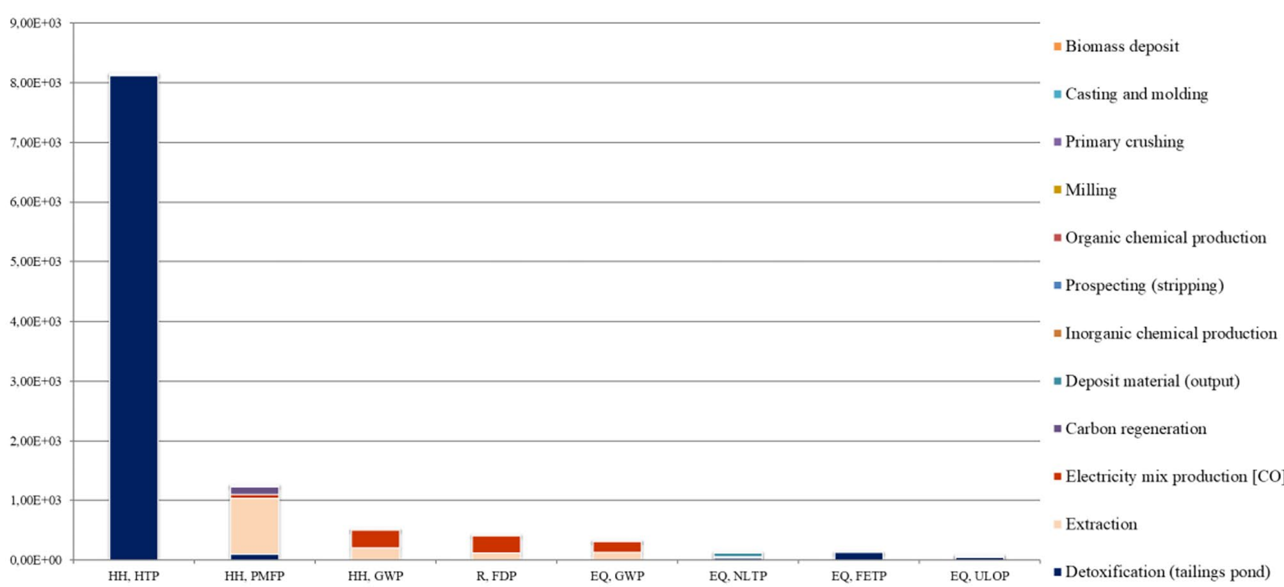

Fig. 8 Environmental performance of open-pit mining under end-point indicators, according to the contribution of each process. HH human health, R resources, EQ ecosystem quality, HTP human toxicity, PMFP particulate matter formation, GWP climate change, FDP fossil depletion, NLTP natural land transformation, FETP freshwater ecotoxicity, ULOP urban land occupation

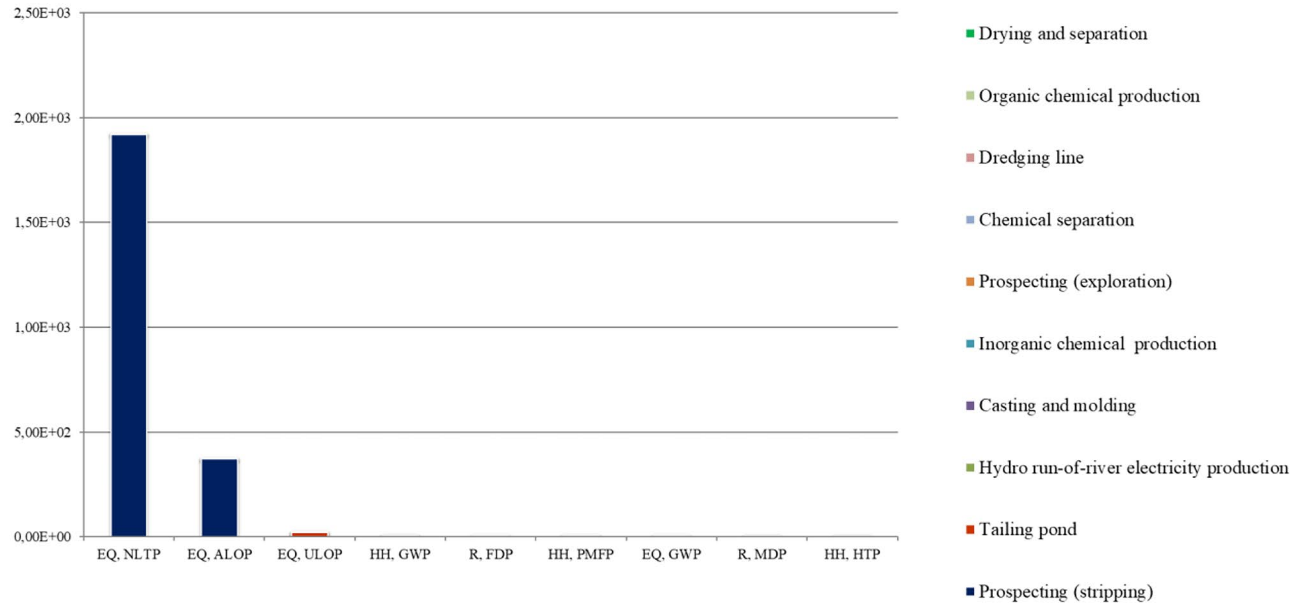

Fig. 9 Environmental performance of alluvial mining under end-point indicators, according to the contribution of each process. HH human health, R resources, EQ ecosystem quality, NLTP natural land transformation, ALOP agricultural land occupation, ULOP urban land occupation, GWP climate change, FDP fossil depletion, PMFP particulate matter formation, MDP metal depletion, HTP human toxicity

environmental impacts are always case-specific and depend very much on local processing conditions implies that these results cannot be automatically applied to other mines, regions, or counties outside Colombia: the same gold mining and processing techniques may well lead to different environmental impacts in different locations. Therefore, the local social, economic, and environmental contexts should be considered when interpreting results.

Possible biomagnification of chemical emissions should be considered in future research. This is important as toxic compounds released to the ecosystem can be spread or consumed by organisms in the food chain which can impact human health. Another recommendation is that the research be extended to the design of the mining supply chain with emphasis on a circular economy approach. This would include a focus on resource efficiency and process optimization strategies (aiming to reduce energy, water, and material consumption) and the management, including potential use, of residues (Cano and Cabezas 2021). Further research is also needed to determine what are the priorities for reducing extraction, considering the socio-economic importance of gold, and key factors such as the stability of its value chain, its substitutability, and its recycling potential. By determining these parameters, strategies can then be adopted such as substitution of the resource for another less scarce resource, increasing material efficiency, and more recycling.

4 Conclusions

The environmental performance of two gold mining process of medium scale (open-pit and alluvial mining) is applied using the life cycle assessment. Environmental impacts were classified and characterized by mid-point impact categories and further aggregated into end-point indicators through the ReCiPe (v. 1.11) methodology. Open-pit mining, which produces more gold (19.05 t/year), has the highest environmental impacts (1.0×10^{04} points), with human health being the most severe damage category, predominately influenced by tailings (87.0%) and then the extraction process (7.5%). The alluvial mining, which produces much less gold (3.1 t/year), has lower impacts (2.4×10^{03} points), with ecosystem quality being the most important damage category due to land use by stripping process with a contribution of the 96.8%. There were only three impact categories where open-pit mining had lower values compared to the alluvial mining: water depletion, agricultural land occupation, and natural land transformation. These results are influenced by data availability. In particular, approximately 70 substances were considered to be present in tailings stage, whereas only 17 substances were considered in alluvial mining (due to confidentiality). This has implications on the comparability of the mining systems in this stage of the process. However, in the alluvial mining, water resource plays an important role in mineral beneficiation, avoiding the use of toxic chemicals in comparison with the open-pit mining technology.

The human health damage from open-pit mining is debatable. This is due to two assumptions; the accumulation of impacts over 100 years and that all waste/emissions are released into the environment after this time. If these are not true, then the actual impacts might vary substantially. Likewise, the most debatable result for alluvial mining is damage on ecosystem quality, given the assumption that the time needed for natural restoration of forest is 40 years, comprising natural land transformation (93% of the natural land transformation resulting from the stripping process) and agricultural land occupation (the areas occupied by extraction activity were equal to 140 hectares/year). However, with proper management of the respective extraction processes, such as a strategic mining planning (operation, closure, and post-closure) or sowing native seeds, these possible impacts could be significantly reduced.

Unfortunately, one of the limitations of life cycle assessments is the life cycle inventory (LCI, see Section 2.2). In the mining sector, inventory databases of chemicals used in mining and mineral processing (e.g., flotation, foaming, emulsifying, coagulation reagents) are not readily available. As a result, studies may be required to generate generic inventory items (e.g. "inorganic chemicals," "organic chemicals") as a proxy for missing data.

To get a clearer picture, further investigation is required on the exact composition and lixiviation of toxic substances in both mining systems as well as the secondary effects of land and water use in alluvial mining. Based on more detailed information, recommendations could be drawn to optimize both mining systems and to reach a well-founded decision on which mining system is preferable, considering the local conditions of each mining site. To aid better decision-making, life cycle costing and social life cycle assessment should be implemented to get an enhanced overview of the positive and negative effects (trade-offs) of the mining activity for all stakeholders involved across the supply chain.

The extraction of mineral deposits implies a reduction of the natural stock, which leads to declining ore grades and a trend of mining deeper deposits requiring the removal of greater quantities of waste material. In turn, more water and energy are required to extract minerals, which typically result in an increased use of fossil fuels. To avoid these impacts, reprocessing of tailings material to extract precious metals that have been disposed in tailings or remove toxic substances is an alternative approach.

The LCA results presented in this study can help decision-making by gold miners, investors, and policy-makers in selecting the gold mining technique with preferred environmental performance given the geologic characteristics and geographical location of the mineral deposit.

The methods used in this paper would allow the sensitivity of environmental performance to some management options to be evaluated. Opportunities for open-pit mining may include the reduction of the percentage of water content in mine tailings by the dewatering process, the implementation of a tailings management system throughout the tailings storage facility (TSF) life, from planning and design to construction, operation, and planning closure according to Adiansyah et al. (2015). A possible alternative for alluvial mining is reprocessing tailings material to extract precious metals (Engels and Dixon-Hardy 2009; Smith 2017) to prevent the reduction of the natural stock of mineral deposits and the stripping of natural areas.

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Data availability Manuscript has not associated data.

Declarations

Conflict of interest The authors declare no competing interests.

Disclaimer This research is focused on studying the sustainability of two different extraction-mining processes such as open-pit and alluvial mining technologies. Data provided by mining companies is confidential information used only to academic purposes.

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Authors and Affiliations

Natalia A. Cano-Londoño[1,5] · Rafael Silva Capaz[2] · Christian Hasenstab[1] · Héctor I. Velásquez[1] · Neil McIntyre[3] · Glen D. Corder[3] · John A. Posada[4]

Rafael Silva Capaz
rafacapaz@unifei.edu.br

Christian Hasenstab
c.h@senstab.net

Héctor I. Velásquez
hivelasq@unal.edu.co

Neil McIntyre
n.mcintyre@uq.edu.au

Glen D. Corder
g.corder@smi.uq.edu.au

John A. Posada
J.A.PosadaDuque@tudelft.nl

[1] Grupo de Investigación en Fenómenos de Superficie-Michael Polanyi, Facultad de Minas, Universidad Nacional de Colombia – Sede Medellín, Medellín 050041, Colombia

[2] Natural Resources Institute, Federal University of Itajubá, Itajubá, Brazil

[3] Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland, Brisbane, QLD 4072, Australia

[4] Department of Biotechnology, Delft University of Technology, van der Maasweg 9, 2629HZ Delft, The Netherlands

[5] Research Group Sustainable Systems Engineering (STEN), Ghent University, Coupure Links 653, 90 0 0 Ghent, Belgium