Assessing digital traceability systems for critical mineral value chains

Aligning upstream and downstream agendas

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Executive summary

The global energy transition and rapid technological change are driving unprecedented demand for critical raw materials (CRM). For the European Union (EU) and its member states, secure and affordable access to these materials is essential to climate, industrial and digital objectives. Yet CRM supply chains are complex, geographically concentrated and increasingly shaped by geopolitical competition and vertical integration strategies. At the same time, environmental, social and governance (ESG) risks in producing countries are under growing scrutiny.

Digital traceability has emerged as a central policy response. This report assesses the feasibility, impacts and strategic implications of advancing digital traceability across CRM value chains, with particular attention to producer-country perspectives and to artisanal and small-scale mining (ASM).

The study combines desk research and stakeholder interviews. It includes a comparative mapping of 27 internationally relevant digital traceability systems, analysing their governance models, operational features and interoperability potential. More than 20 semi-structured interviews were conducted with solution providers, supply chain actors, standard setters, government representatives and civil society. The findings were validated through a multi-stakeholder roundtable held in February 2026, where feedback on key draft findings was gathered and integrated into the final report.

Key Findings

- **Traceability is a tool, not a substitute for due diligence.** New technologies make it technically feasible to track minerals and associated ESG data throughout the entire supply chain from extraction to processing, manufacturing and recycling. However, while digital systems can generate and transmit data, they do not in themselves ensure responsible sourcing. Their effectiveness depends on governance, verification and how information is used to guide risk mitigation and decision-making.
- **Interoperability is the key enabler for scale.** CRM supply chains vary widely by mineral, extraction method and trading structure. Combined with overlapping standards and regulations, this diversity has produced a fragmented ecosystem of traceability systems concentrated in specific regions or segments. Uniform mine-to-product tracking across all supply chains is rarely realistic. Scalability depends on interoperability – shared identifiers, data formats and exchange protocols that allow information to move across systems and jurisdictions. Interoperability is as much a governance issue as a technical one, requiring awareness, trust and collaborative design.

- **Producer-country alignment is critical.** Traceability initiatives often reflect downstream regulatory priorities more than upstream realities. In many producing countries, traceability is perceived primarily as an administrative burden. Yet emerging national mineral governance platforms demonstrate how digitised state systems can strengthen oversight, revenue collection and regulatory control. Embedding traceability within such domestic architectures can align global transparency demands with national development objectives. Meaningful producer-country engagement and investment in enabling infrastructure are therefore essential.

- **Inclusion of ASM requires pragmatic design.** Rigid end-to-end traceability requirements risk excluding ASM, a sector that supports millions of livelihoods and contributes significantly to global CRM supply. Feasible approaches prioritise progressive improvement over binary compliance models and begin at aggregation points rather than insisting on complete granular tracking from the mine site. Inclusion also depends on complementary measures and incentives, such as access to finance, fair pricing and institutional support.

- **Traceability costs and benefits must be balanced.** Downstream actors often capture benefits in terms of compliance, supply and inventory management and reputation, while upstream actors bear disproportionate burdens. Long-term viability requires reframing traceability as shared operational infrastructure that supports inventory management, risk management and supply chain resilience. To avoid reinforcing existing asymmetries, hybrid financing models and improved cost-sharing arrangements will be necessary.

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List of acronyms

3T	Tin, tantalum and tungsten
AFP	Analytical Fingerprint
ANAFIC	National Agency for Local Government Financing
API	Application Programming Interface
APO	Analytical Proof of Origin
ARM	Alliance for Responsible Mining
IASI	Aluminium Stewardship Initiative
AM	Artisanal Mining (AM)
ASM	Artisanal and Small-scale Mining
BGR	German Federal Institute for Geosciences and Natural Resources
CAHRAs	Conflict-Affected and High-Risk Areas
CBAM	Carbon Border Adjustment Mechanism
CEN	EU Committee for Standardisation
CMSI	Consolidated Mining Standard Initiative
CoC	Chain of Custody
CRMA	EU Critical Raw Materials Act
CRM	Critical Raw Materials
CS3D	EU Corporate Sustainability Due Diligence Directive
CSRD	Corporate Sustainability Reporting Directive
DBP	Digital Battery Passport
DLT	Distributed Ledger Technology
DRC	Democratic Republic of the Congo
EBSI	European Blockchain Services Infrastructure
EGC	Entreprise Générale du Cobalt
EITI	Extractive Industries Transparency Initiative
EPRM	European Partnership for Responsible Minerals
ERP	Enterprise Resource Planning
ESG	Environmental, Social and Governance
ESPR	Ecodesign for Sustainable Products Regulation
ESRS	European Sustainability Reporting Standards
EU	European Union
EV	Electric Vehicle
FDA	US Food and Drug Administration
FNDL	National Fund for Local Development (Guinea)
FODEL	Local Economic Development Fund (Guinea)
FSA	Food Standards Agency
GDST	Global Dialogue on Seafood Traceability
GRI	Global Reporting Initiative
GS1	Global supply chain standards organisation
GISTM	Global Industry Standard on Tailings Management
ICGLR	International Conference on the Great Lakes Region
IFC	International Finance Corporation

IFT	Institute of Food Technologists
IoT	Internet of Things
IPFS	InterPlanetary File System
IRMA	Initiative for Responsible Mining Assurance
ISEAL	International Social and Environmental Accreditation and Labelling Alliance
IWA	International Workshop Agreement
LBMA	London Bullion Market Association
LME	London Metal Exchange
LPPM	London Platinum and Palladium Market
LSM	Large-Scale Mining
MOSES	Mineral Output Statistical Evaluation System (Zambia)
OACPS	Organisation of African, Caribbean and Pacific States
OEMs	Original Equipment Manufacturers
OECD	Organisation for Economic Co-operation and Development
PDO	Protected Designation of Origin
RBA	Responsible Business Alliance
RBTP	Responsible Business Transparency Protocol
RMAP	Responsible Minerals Assurance Process
RMI	Responsible Minerals Initiative
SaaS	Software-as-a-Service
SEM 2.0	Sistema de Exportaciones Mineras (Chile)
SIRA	Stable Isotope Ratio Analysis
SSM	Small-Scale Mining
TSM	Towards Sustainable Mining
UNCTAD	United Nations Conference on Trade and Development
UNTP	UN Transparency Protocol
US	United States
WGC	World Gold Council

Introduction

The global energy transition, rapid technological innovation and continued industrialisation and urbanisation in emerging economies are driving unprecedented demand for minerals. Access to these resources has become a strategic concern, prompting governments and intergovernmental organisations to identify “critical raw materials” (CRM)[1]and develop policies to secure supply, stimulate investment and promote more sustainable practices. For the EU, whose climate, industrial and digital objectives rely heavily on secure and affordable access to these materials, these dynamics have elevated mineral supply security to a central strategic priority.

For many of these minerals, supply is complex, opaque, constrained and increasingly uncertain. Structural factors include the concentration of significant CRM extraction in high-risk jurisdictions. They also reflect the long-term strategy of some countries, particularly China, to vertically integrate mining, processing and manufacturing, thereby clustering midstream capacity and increasing leverage over other countries’ security of supply. At the same time, international collaboration that initially helped diffuse supply chain risks, has given way to more transactional trade and industrial policies, notably under the second Trump administration. Together, these shifts risk further marginalising the EU in efforts to secure reliable mineral supply.

In parallel, the race to scale up mineral production has intensified concerns about environmental, social and governance (ESG) impacts in producing countries. For the EU, the promotion of standards and traceability has emerged as a central strategy for engaging with global mineral markets, seeking to enhance supply predictability while reducing political and investment risks and mitigating adverse impacts. At present, policy attention is heavily focused on traceability, as advances in digital technologies make it possible to trace minerals and related ESG data from extraction through processing, manufacturing, use and recycling.

Effective digital traceability systems sit within a wider governance ecosystem. Standards define expectations for responsible practices, while due diligence processes guide the identification, prevention and mitigation of risks and impacts. Traceability tools capture and transmit the data needed to support and verify these efforts. However, in the absence of appropriate policies and accompanying measures, the benefits of traceability may be unevenly distributed. While some actors gain market access and strategic advances, others – particularly in producer countries – may face additional costs, administrative burdens, or compliance barriers that risk reinforcing exclusion and asymmetries.

This report analyses the potential benefits and drawbacks of advancing digital traceability across different stakeholder groups, including government actors, artisanal and small-scale miners, large-scale mining companies and mineral sourcing firms. It aims to deepen understanding of how traceability can simultaneously address downstream demand for transparency, ESG compliance and supply chain resilience, while supporting producer country priorities such as improved oversight of mineral flows, revenue management and opportunities for value addition.

The report is structured as follows. **Chapter 1** sets out the context, defines traceability, explains key drivers and their relationship with due diligence and describes the methodology, including the selection of digital solutions, stakeholders and country cases. **Chapter 2** reviews the ESG standards landscape for critical minerals and analyses how traceability is embedded in and can support convergence across ESG frameworks.

Chapter 3 develops an analytical typology of digital traceability architectures, including verification mechanisms and chain-of-custody models. **Chapter 4** provides a comparative mapping of selected digital traceability systems, examining their scope, governance arrangements, implementation approaches and data management models. **Chapter 5** assesses feasibility, focusing on technical and infrastructure constraints (particularly in ASM contexts), interoperability challenges, financial and economic viability and governance and verification capacity.

Chapter 6 assesses the impacts of expanding traceability from a producer-country perspective, analysing implementation challenges, positive and adverse effects, implications for mineral governance, revenue mobilisation and value addition agendas and the strategic considerations shaping producer-country engagement.

Chapter 7 presents recommendations for international cooperation to promote meaningful, interoperable, inclusive and financially sustainable traceability. **Chapter 8** concludes by synthesising key findings on fragmentation, producer-country alignment, ASM inclusion, financing challenges and the conditions required to realise traceability's full potential in CRM value chains.

1. Context, scope and methodology

1.1. Defining traceability

Drawing on existing literature[2], this study defines traceability as the systematic process of recording, transferring and accessing verified information on the origin, conditions of production, manufacturing and trade, geographical path, chain of custody and physical evolution of materials or products as they move through a value chain. Traceability acts as a vehicle for information, linking each actor and stage of production. It supports responsible supply chain practices by helping companies map supply chains, verify sources and generate the data needed for effective risk management and accountability.

Several related terms are often used when discussing responsible supply chain practices, especially those linked to information disclosure. These terms are frequently used interchangeably, which creates confusion. The OECD's definitions provide clarity:

- **Due diligence** – As defined in the 2023 OECD Guidelines for Multinational Enterprises on Responsible Business Conduct, is "the process through which enterprises can identify, prevent, mitigate and account for how they address their actual and potential adverse impacts as an integral part of business decision-making and risk management systems"[3].
- **Supply chain transparency** – The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD Due Diligence Guidance) defines supply chain transparency functionally, stating that enterprises "should introduce a supply chain transparency system and assess conflict-related risks in the supply chain. The supply chain transparency system should include a) a chain of custody or traceability system; b) identification of the smelters/refiners in the company's supply chain"[4].
- **Chain of custody (CoC)** – The OECD Due Diligence Guidance defines chain of custody as "a record of the sequence of entities which have custody of minerals as they move through a supply chain"[5].

These concepts are interdependent but not identical: **CoC** is about generating information flows along the chain, **supply chain transparency** concerns how that information is disclosed and **due diligence** uses such information as one input into broader risk identification, prevention, mitigation and remediation.

1.2. Drivers of traceability uptake in CRM supply chains

The uptake of traceability systems in CRM supply chains is driven by four interconnected system-level drivers.

First, structural demand growth driven by the energy transition is intensifying concerns over **long-term supply security.** While climate ambition is increasingly uneven across jurisdictions, the broader dynamics of electrification, decarbonisation and industrial transformation continue. These trends depend on secure and sustainable access to CRM that underpin low-carbon technologies, from lithium, nickel and cobalt in electric vehicle batteries to rare earth elements used in wind turbines. Demand for these materials is projected to increase significantly, placing sustained strain on production capacity and global supply chains[6]. In this context, traceability gains relevance as a tool for improving visibility, oversight and strategic supply management.

Second, supply chain resilience and circular economy strategies are generating additional **governance demands** for traceability. As CRM supply chains expand and diversify, unmanaged social, environmental and geopolitical risks can disrupt production, restrict market access and undermine clean energy deployment[7]. The ability to credibly demonstrate compliance with ESG standards is increasingly central to maintaining buyer confidence, meeting regulatory requirements and securing long-term supply relationships. In parallel, governments and multilateral institutions increasingly frame circularity as a means of reducing environmental impacts, while mitigating exposure to external shocks. As secondary material flows expand, reliable information becomes essential for governing recycled inputs, identifying provenance, assessing material characteristics and ensuring sourcing practices meet applicable standards[8]. This increases demand for traceability systems that can support resilient and well-regulated trade in both primary and recycled materials.

Third, even as global **regulatory momentum** is weakening, traceability remains a key compliance enabler within the EU's evolving sustainability framework. Several regulatory instruments, such as the EU Conflict Minerals Regulation, Battery Regulation, Critical Raw Materials Act (CRMA) and Corporate Sustainability Due Diligence Directive, increase expectations for supply chain transparency and due diligence (see section 2.1.). While traceability is increasingly referenced across these frameworks, its impact on implementation and uptake varies depending on how obligations are framed and enforced. In some cases, regulatory proposals have been politically contested, with concerns raised that mandatory requirements can be burdensome or difficult to operationalise in complex supply chains[9].

Fourth, **technological innovation and digitalisation** in supply chain management are accelerating the uptake of traceability systems. New solutions are used to reduce reliance on intermediaries, enhance transparency and trust, facilitate information exchange and minimise contamination risks through automated sensing, data capture and cloud-based analytics,[10] as well as to make records harder to tamper with and increase accountability for the information reported[11].

1.3. How traceability and due diligence work together

Traceability and due diligence should be understood as separate but complementary systems, in which traceability functions as an enabling mechanism. Traceability provides the visibility needed for companies to identify risks within their supply chains. Due diligence builds on that visibility by evaluating the significance of identified risks, determining appropriate responses and monitoring the effectiveness of mitigation measures over time. The OECD Due Diligence Guidance is widely recognised as the core framework for mineral supply chain due diligence. While it does not prescribe the use of traceability systems, it emphasises that the type and depth of information gathered should be proportionate to the level of risk. In high-risk contexts, more advanced or granular traceability mechanisms may be required to support meaningful due diligence, whereas in lower-risk settings, simpler CoC mechanisms may be sufficient.

The Guidance also defines a set of "red flags" related to mineral origin, transit routes and supplier circumstances. These trigger enhanced due diligence, requiring companies to gather more detailed information on business relationships and sourcing conditions. Such processes depend on collaboration across supply chain tiers: upstream actors generate data on origin and production conditions, midstream actors verify and consolidate the data, and downstream actors use it to inform risk assessment, reporting and disclosure.

Traceability systems can make risk-based due diligence more manageable and cost-effective by facilitating automated data collection, aggregation and reporting. However, their effectiveness depends on the quality, reliability and relevance of the underlying data (see Section 5.4. and 6.3.) as well as on companies' capacity to interpret findings and act upon them.

Implementing due diligence: uneven compliance burdens

The OECD Due Diligence Guidance underlines the need for coordination and cooperation so that due diligence responsibilities and costs are shared fairly, upstream actors are not exposed to disproportionate administrative demands and the information they generate is properly recognised and valued by downstream companies[12].

The growing number of due diligence regulations (see Section 2.1.) increases compliance demands across global supply chains. Many actors in the Global South – particularly smaller operators – lack the financial resources, technical expertise and regulatory familiarity needed to meet expanding documentation and reporting expectations. Without targeted upstream support, these dynamics can lead to exclusion and disengagement, rather than to improved practices.

Due diligence and traceability approaches must therefore be designed with implementability in practice. If suppliers cannot meet or understand requirements in practice, due diligence and traceability may unintentionally reinforce the risks they aim to mitigate.

Cobalt supply chains in the **Democratic Republic of the Congo** (DRC) illustrate how traceability and due diligence interact. Various initiatives have sought to support responsible sourcing by documenting provenance and site-level practices[13]. In the absence of reliable upstream transparency, however, some downstream companies, such as Umicore, have decided to exclude artisanal and small-scale mined cobalt to limit legal and reputational exposure[14]. Such disengagement has immediate consequences for market access and longer-term implications for local economic development.

Exclusion often occurs when provenance information is used as a substitute for robust due diligence. When an entire country or region is labelled “high risk”, downstream actors may avoid sourcing from that origin altogether, sidelining suppliers regardless of conditions at specific sites.

This pattern is evident in the DRC, but similar dynamics can arise in other geopolitical contexts. Without robust due diligence capable of distinguishing between risks that can be managed and those that cannot, traceability can inadvertently enable broad-brush exclusion instead of supporting more targeted and responsible engagement.

1.4. The role of digital traceability

Digital technologies can streamline traceability by automating data capture and management, but they cannot on their own ensure responsible sourcing or improve conditions at production sites. A supply chain may be digitally traceable to a specific mine while providing little insight into labour practices, environmental management or community impacts. Risks flagged by digital systems are only a starting point; companies must still analyse the information and engage stakeholders to identify and address actual or potential impacts.

The OECD highlights the two-way relationship between traceability and due diligence[15]. Traceability information can refine risk assessment and prioritisation, while due diligence findings determine the appropriate scope and depth of traceability systems in a given context.

For traceability to meaningfully support due diligence, the information collected must be relevant to the risks communities actually face. Global indicators such as greenhouse gas emissions may be useful, but they do not capture many local environmental and social harms. In the DRC, for instance, communities near cobalt and copper operations face immediate risks from dust exposure, heavy metal contamination and water pollution, despite the country hosting one of the world’s largest tropical forest carbon sinks[16]. In northern Chile, long-standing copper production and expanding tailings infrastructure have exposed indigenous communities to toxic metals[17]. In such contexts, a focus on emissions data can overlook the most material risks on the ground. Without context-specific, risk-relevant data, traceability systems cannot provide the information needed for effective due diligence.

1.5. Methodology

This report uses a qualitative research approach that combines a desk review with stakeholder interviews. The desk review covered academic studies on traceability and ESG in mineral supply chains, comparative analyses of sustainability and traceability systems, policy briefs from multilateral and regional organisations, ESG standards and information from traceability providers and certification schemes. The research involved a comparative mapping of a diverse set of digital traceability systems in order to understand the state of play in the field, in terms of scope, governance arrangements, operationalisation, data management and interoperability.

Building on this literature, the study conducted over 20 semi-structured interviews with a diverse set of stakeholders across the CRM value chain, including traceability solution providers, standard setters, supply chain actors, government representatives and civil society organisations. Interview questions focused on how traceability contributes to due diligence processes and outcomes, the advantages of taking part in traceability solutions, the limitations and challenges of implementing them, and what is needed to strengthen the role of traceability in reducing adverse impacts in mineral supply chains.

Key findings were validated during a roundtable with 15 participants representing public sector actors from European and producer country governments, private sector and industry associations, as well as standard-setting organisations and civil society. The roundtable was held in February 2026 at the “Investing in African Mining Indaba” Conference in Cape Town, South Africa, in the context of a side event organised by the GIZ on “Unlocking Africa’s Resource Potential for Responsible and Resilient Supply Chains”. During this session, feedback and inputs on key draft findings were gathered and subsequently integrated into the final report.

Selection of digital traceability systems

Given the fast pace of technological change and evolving value chains, new digital traceability tools are continuously developed. To ensure focus and analytical depth, the study selected 27 digital traceability systems that balance diversity and relevance in line with the study’s objectives (see Chapters 3 and 4 for a typology and comparative mapping of the selected solutions). Selected tools meet all of the following criteria:

- Cover critical minerals (or have the potential to do so);
- support, enable or inform due diligence, ESG assurance or compliance processes;
- Use digital technologies;
- Address multiple stages of the supply chain (i.e. extraction, processing, trading, manufacturing, or market access);

- Have an international scope (not limited to a single country or company); and
- Provide sufficient publicly available information.

In addition, selected tools meet at least one of the following criteria:

1. Demonstrated maturity beyond conceptual design: systems are deployed, piloted, referenced, or actively used in critical mineral supply chains; or
2. New, original or innovative systems with strong potential for technical interoperability and/or scalability.

The systems analysed in this study constitute a non-exhaustive and intentionally heterogeneous selection, representing diverse aspects of the traceability ecosystem. All selected systems are directly or indirectly linked to digital traceability, either by implementing traceability, enabling it through infrastructure, standards, or governance, or by analysing traceability data and systemic risks. This study excludes tools that are unrelated to traceability, such as ESG reporting platforms, tools focused solely on data reporting without traceability capabilities and advisory services.

Stakeholder selection

To complement the desk review, the study engaged stakeholders with direct experience of digital traceability in critical mineral supply chains and its effects on ESG performance. Stakeholders were selected to reflect different countries of operation, different roles along the supply chain (from artisanal and industrial production to downstream use), and whether they are directly affected by mineral supply chains or influence them through regulation, standard-setting or community representation.

Five main stakeholder groups were included: traceability solution providers, supply chain actors, government representatives, civil society organisations and standard-setting bodies. Solution providers contributed insights on system design, data management, governance, feasibility and contribution to due diligence. Supply chain actors (downstream companies, smelters and refiners, industrial mining companies and an ASM cooperative) shared experiences of using traceability tools, reflecting on benefits, costs, limitations and implementation challenges. Government officials from producer countries discussed national traceability requirements and systems, expectations of private initiatives and perceived impacts on responsible mining. International and national civil society organisations reflected on impacts for communities and workers and on how to strengthen traceability's role in reducing adverse impacts. Standard-setting bodies provided perspectives on the ways traceability operates within certification systems, the value it adds to due diligence and key opportunities and constraints they observe.

Country cases

The study examines country cases to capture diverse perspectives and practices that offer broader lessons on the technical and financial feasibility, as well as the economic and political economy impacts and potential, of digital traceability. The depth of analysis varies by country: in some, the study explores specific traceability experiences in detail, while in others it adopts a more exploratory view of emerging approaches and debates. Countries were selected to reflect differences in the presence of critical minerals, the balance between large-scale mining (LSM) and ASM, the strength of regulatory frameworks, oversight and enforcement, levels of fragility, existing traceability solutions and connectivity as well as digital literacy. The study includes perspectives and examples from Chile, DRC, Tanzania, Guinea and Indonesia.

2. ESG standards and traceability

2.1. ESG standards

ESG standards in the mining sector are rapidly evolving. In 2022, the German Federal Institute for Geosciences and Natural Resources (BGR) published the study *Sustainability Standard Systems for Mineral Resources: A Comparative Overview*, offering a comprehensive mapping of sustainability standards across the minerals sector.[18] The study found that standard systems are gradually expanding in membership, global reach, range of commodities covered and overall ESG scope. It observed an ongoing evolution of due diligence approaches to encompass broader ESG criteria and multiple segments of the supply chain. However, the study also concluded that transparency and geographic coverage remain limited and that wider societal and circular-economy objectives are insufficiently addressed.

Despite continued sophistication of standards, the ESG landscape today remains largely voluntary and dominated by company-driven schemes. This results in fragmentation and uneven implementation, with practices centred on periodic audits and risk-screening processes rather than continuous, data-driven performance monitoring.

Towards more convergence

In recent years, European due diligence regulations and rising investor expectations have started to drive a closer integration of ESG assurance, digital traceability and regulatory compliance. The ESG landscape in Europe and beyond is reshaped by four ongoing dynamics that push towards convergence of standards and closer connection of ESG assurance systems with emerging EU regulatory and data infrastructures.

1. **Regulatory consolidation** is driven by a suite of EU instruments (see Box 2) that progressively turn voluntary reporting and responsible sourcing practices into binding obligations on due diligence, sustainability performance, risk management and data disclosure across CRM value chains. Together, these measures amount to the most far-reaching attempts globally to regulate the ESG dimensions of CRM supply chains, shaping practices not only for EU-based operators but also for international suppliers that seek access to the European market.
2. **Standard consolidation** is exemplified by the Consolidated Mining Standard Initiative (CMSI), which integrates and harmonises the core requirements of existing responsible mining frameworks, including the Copper Mark, the International Council on Mining and Metals (ICMM) Mining Principles, the Mining Association of Canada's Towards Sustainable Mining (TSM) program and the World Gold Council's (WGC) Responsible Gold Mining Principles (RGMPs).

3. **Technical alignment** is reflected in a new generation of standards such as ISO 23664 *Traceability of Rare Earth Elements*, which specifies requirements and gives guidance on the design and use of traceability for REE supply chains. Also relevant are ISO Project Committee (ISO/PC) 348 *Sustainable Raw Materials* and ISO International Workshop Agreement (IWA) 45 *Sustainable Critical Minerals Supply Chains*. The former develops criteria for sustainability across raw material value chains, while the latter provides its analytical foundation. Both inform the European Committee for Standardisation (CEN) Technical Committee (TC) 472 *Rare Earths* and CEN/TC 477 *Sustainable Raw Materials* under the CRMA.

4. **Digital integration** is increasingly shaped by digital product passports (DPPs), emerging registry systems such as the Global Battery Alliance (GBA) Battery Passport (see Box 3), and pilots by traceability providers such as Circulor and Minespider, which integrate blockchain-based traceability with ESG and carbon-footprint data. These developments build on foundational global data standards from organisations such as GS1, enabling interoperable supply chain practices through barcode-based product identification (e.g. GTINs), shared data models and multi-stakeholder coordination. Complementing these efforts, the UN Transparency Protocol (UNTP) (see Box 2) defines common data standards, verifiable credential formats and interoperable protocols to enable cross-platform compatibility.

Box 1: Key EU instruments shaping ESG and traceability in CRM supply chains

- **Corporate Sustainability Due Diligence Directive (CSDDD or CS3D, 2024/1760):** Establishes mandatory human rights and environmental due diligence obligations for large in-scope companies across their value chains, embedding the OECD Due Diligence Guidance in EU law. Effective implementation depends on upstream visibility and reliable traceability information. The Directive is currently subject to an “omnibus” amendment process that may adjust scope, thresholds and timelines.[19]
- **Corporate Sustainability Reporting Directive (CSRD, 2022/2464):** Requires large companies to disclose ESG information using the European Sustainability Reporting Standards (ESRS), including data relevant to sourcing, supply chain risks and material traceability. Elements of scope and timelines are also subject to potential omnibus amendments.

- **Critical Raw Materials Act (CRMA, 2024/1252):** Establishes a framework to strengthen the EU's secure and sustainable supply of CRM, including benchmarks for domestic extraction, processing and recycling. While not mandating traceability systems, it reinforces the importance of origin-related risk analysis and supply chain visibility.
- **Conflict Minerals Regulation (2017/821):** Requires EU importers of tin, tantalum, tungsten and gold (3TG) above specified annual volume thresholds to conduct supply chain due diligence in line with the OECD Due Diligence Guidance. Compliance requires chain-of-custody information and documentation of sourcing practices.
- **Ecodesign for Sustainable Products Regulation (ESPR, 2024/1781):** Establishes a horizontal for framework sustainability requirements across a wide range of products and provides the legal basis for digital product passports (DPP). DPPs will progressively require product-level information on material composition, circularity, environmental performance and compliance, including for CRM-intensive product groups.
- **Battery Regulation (2023/1542):** Sets sustainability, safety and circularity requirements for certain batteries placed on the EU market, including carbon-footprint thresholds, recycled-content obligations and due diligence requirements for certain raw materials such as cobalt, lithium, nickel and graphite. It introduced the digital battery passport (DBP) to enhance lifecycle transparency and ESG data exchange.
- **EU Strategy on Standardisation (2022/31):** Sets out the European Commission's strategic priorities for European standardisation in support of the Green Deal, digital transition and industrial resilience, including work relevant to sustainability, circularity and CRM.

It is important to note that regulatory consolidation does not mean harmonisation. Fragmentation remains a challenge. Regulatory frameworks vary significantly in the extent to which they specify the role of traceability. Some mandate comprehensive digital passports and detailed supply chain traceability, most notably the EU Battery Regulation and its battery passport requirements[20], while others focus more broadly on due diligence and supply security without specifying how traceability should be implemented, such as the EU CRMA. This leads to uneven adoption among companies, as they navigate differing expectations on data granularity and enforcement capacities. For example, the Battery Regulation, CRMA and Conflict Minerals Regulation all rely on member states to develop their own penalty frameworks, which can create inconsistent enforcement outcomes[21].

Box 2: The UN Transparency Protocol (UNTP)

The UNTP is a digital interoperability standard being developed by the UN Centre for Trade Facilitation and E-Business (UN/CEFACT). It provides a shared protocol and common data architecture that enables diverse software systems – including traceability platforms, digital product passports and ESG reporting tools – to exchange verified supply chain and sustainability information in a trusted and machine-readable format.

UNTP's design helps supply chain actors share ESG evidence and provenance data while respecting confidentiality and reducing the costs of demonstrating compliance with multiple overlapping standards and regulations[22].

Several governments, major industry associations and standard-setting organisations support the initiative and have launched pilots and interoperability testing. These efforts explore use cases in critical minerals, electronics and automotive value chains, illustrating how UNTP can facilitate cross-border compliance and data exchange across markets.

At the same time, awareness and practical understanding of UNTP remain uneven among both companies and producer-country institutions. Many stakeholders are unclear about its operational relevance and urgency. Broader uptake therefore depends not only on technical development, but also on outreach, capacity building and real-world testing to ensure that agreed standards function effectively in practice.

The current ESG landscape for critical minerals

The most widely recognised ESG and due diligence standards now form a multilayered system, with each typically addressing one or more of the following four layers:

1. **Cross-sector due diligence frameworks** such as the OECD Guidelines for Multinational Enterprises, the OECD Due Diligence Guidance and the UN Guiding Principles on Business and Human Rights (UNGP) define the baseline process for risk-based due diligence in mineral supply chains.
2. **Operational ESG standards for mining and processing** translate due diligence expectations into auditable site-, facility- or corporate-level requirements. They define measurable performance criteria across environmental, social, governance and safety dimensions. Examples include the Responsible Minerals Initiative (RMI) through its Responsible Minerals Assurance Process (RMAP), the ICMM Mining Principles, the CMSI, the Initiative for Responsible Mining Assurance (IRMA), Mining Association of Canada's

Towards Sustainable Mining (TSM) and the Global Industry Standard on Tailings Management (GISTM). Consolidated assurance initiatives such as CERA 4in1 – an industry-led framework developed in the context of European critical raw materials policy discussions – seek to harmonise and streamline compliance across multiple recognised ESG standards through a single integrated audit process.

3. **Mineral-specific standards** such as the Aluminium Stewardship Initiative (ASI) and the Copper, Nickel and Zinc Marks tailor ESG requirements to value chain characteristics of individual metals, linking site-level audits to chain-of-custody or product claims.

4. **Financial and market-driven instruments**, including the London Metal Exchange (LME) Responsible Sourcing Requirements (RSR), the London Platinum and Palladium Market (LPPM) Responsible Sourcing Guidance (LSG), RMI conformant smelter lists, and emerging disclosure expectations linked to the EU Carbon Border Adjustment Mechanism (CBAM), connect ESG and due diligence assurance directly to market access and pricing by making disclosure requirements conditions for trading and supplier qualification.

Table 1: Layers of ESG and Due Diligence Governance in Mineral Supply Chains

Layer	**Description**	**Main actors & examples**
Cross-sector due diligence frameworks	Provide the procedural backbone for due diligence and human-rights-based risk management.	OECD Due Diligence Guidance UNGP
Sector-wide or multi-mineral standards	Establish common ESG performance benchmarks throughout the extraction and/or processing stages of the mineral value chain, across a range of commodities.	CERA 4in1 CMSI ICMM - MP IRMA RMI - RMAP MAC – TSM GISTM
Mineral-specific initiatives	Tailor ESG and due diligence criteria to the characteristics and value chains of individual metals, linking site-level assurance to chain-of-custody or product-level claims.	ASI Copper Mark Nickel Mark Zinc Mark
Financial- and market-driven instruments	Tie ESG and due diligence assurance to market participation, pricing and investment by making disclosure requirements conditions for trading,	EU - CBAM LME - RSR LPPM - RSG

	supplier qualification and product eligibility.	

Inclusion of artisanal and small-scale mining

A persistent limitation of many ESG standards is their limited accommodation of ASM, even though this subsector produces a substantial share of critical minerals such as cobalt, tin and tantalum[23]. Two notable models provide guidance on how to integrate ASM in responsible supply chains:

- **CRAFT** (Code of Risk-mitigation for Artisanal and Small-scale Mining Engaging in Formal Trade), developed by the Alliance for Responsible Mining (ARM) in 2018 and updated in 2021 in collaboration with Resolve, provides an OECD-aligned, stepwise due diligence framework for ASM[24]. It enables ASM operators to demonstrate compliance with due diligence requirements and facilitates the generation of structured supply chain data that can interface with traceability systems.
- **Entreprise Générale du Cobalt (EGC)**, established in 2019 in the DRC as a subsidiary of the state-owned mining company *Gécamines*, seeks to formalise and channel ASM cobalt production through regulated trading structures. It combines bag-and-tag traceability, cooperative formalisation and digital tracking pilots to align ASM cobalt exports with national regulation and international due diligence expectations. The initiative remains at the pilot stage, with limited operational output and ongoing testing of traceability and formalisation models[25].

2.2. Traceability in ESG standards

Across mineral value chains, ESG standards refer to traceability in different, partially overlapping ways rather than as a single, harmonised concept[26].

In simplified form, three main traceability functions can be distinguished.

1. **Responsible-origin assurance** models treat traceability as the ability to demonstrate that material originates from a mine, facility or site audited against defined ESG requirements. Several standards certify responsible production but do not, in themselves, require or facilitate the tracking of material beyond the certified site. The model is influential because it is scalable, audit-compatible and provides a convenient building block for responsible sourcing claims.

   Examples include site-level performance standards such as the ASI Performance Standard and Responsible Steel, mineral-specific schemes like The Copper Mark and WGC’s RGMPs and broader frameworks such as IRMA, CERA 4in1 and CMSI.

2. **Due diligence reporting** approaches focus on generating structured information on suppliers, intermediaries, transport routes and other actors to enable companies to identify, assess and mitigate ESG risks across multiple tiers. This function underpins compliance with regimes like EU CS3D and CSRD by generating data for due diligence reporting but does not necessarily involve material-level traceability.

   Examples include the CRAFT Code for ASM due-diligence data, the RMI Cobalt Refiner Standard and RMAP for upstream supply chain mapping, the EGC responsible sourcing framework for ASM cobalt in the DRC and the International Finance Cooperation (IFC) Performance Standards 1 and 2 on ESG risk management and labour conditions.

3. **Chain of custody (CoC)** models require materials – or their documented flows – to be followed through production, processing and trade, using mechanisms such as physical tagging, digital identifiers, input–output accounting and audit-ready records (see further Chapter 3). CoC traceability is increasingly built into digital product passports and EU regulatory systems, but remains complex to implement at scale.

   Examples include the ASI and ResponsibleSteel CoC Standards, electronics recycling schemes such as the R2 Standard and e-Stewards and technical standards like ISO 23664 (rare earth traceability).

A growing emphasis on the reliability, comparability and structured disclosure of ESG data underpins all three functions. This ensures that it is clearly linked to specific operations, can be verified and benchmarked across companies and supports auditable due diligence claims. Clear rules on data governance, formatting and transparency are central to this function.

Examples of such efforts include the European Sustainability Reporting Standards (ESRS) and sector-specific guidance such as Sector Standard 14 of the Global Reporting Initiative (GRI) for mining and related mineral-supply chain reporting practices.

2.3. Towards an integrated ESG-traceability ecosystem

This analysis indicates a gradual consolidation of ESG standards and traceability systems into one ecosystem. ESG assurance systems increasingly generate quantifiable data that can be embedded in DPP or blockchain registries, allowing sustainability information to move with CRM along the supply chain[27].

Credible end-to-end traceability in CRM supply chains will depend on how complementary functions work together: ESG standards define principles and due diligence expectations;

technical standards and data infrastructures translate these into measurable, verifiable flows of materials and information; regulatory instruments make them binding and enforceable.

Effective traceability is therefore both a governance and systems-engineering challenge: gaps in upstream data, interoperability or ASM inclusion can undermine the integrity of the whole chain. As EU initiatives on DPP, due diligence and CRM monitoring advance, their coherence with ESG and technical standards will largely determine the credibility and inclusiveness of responsible sourcing systems.

Box 3: Global Battery Alliance and the Battery Passport

The Global Battery Alliance (GBA) is a public–private, multi-stakeholder platform founded in 2017 at the World Economic Forum. It brings together governments, civil society, industry actors (including mining, materials, battery cell producers and OEMs), academia and international organisations to pursue a sustainable, circular and socially responsible global battery value chain by 2030.

A central initiative of the GBA is the Battery Passport, an emerging global sustainability reporting and certification framework for batteries. Rather than a stand-alone scheme, it defines common sustainability indicators (e.g., carbon footprint, material provenance, responsible sourcing, social metrics) and data exchange principles to help harmonise reporting across different systems and jurisdictions.

The GBA Battery Passport has been developed in close alignment with the digital battery passport requirements introduced under the EU Battery Regulation. Under this Regulation, from 2027 onwards, electric vehicle batteries, industrial batteries and light-means-of-transport batteries placed on the EU market must be accompanied by a digital battery passport. This passport must be accessible via a QR code and contain specified information on the battery’s lifecycle, carbon footprint and other sustainability-related parameters.

Since 2023, the GBA has convened pilots and proof-of-concept exercises across the value chain. In 2026 it has begun larger operational trials with around 15 consortia of value chain participants to test sustainability reporting, benchmarking and interoperability with digital tools in real-world settings[28].

3. Traceability system architecture

3.1. An analytical typology of digital traceability systems

There exists considerable ambiguity regarding the roles and features of different traceability systems, which are frequently conflated despite serving distinct functions. This lack of differentiation hinders effective assessment and comparison. To address this issue, this study distinguishes four complementary categories. These differ in objectives, governance models and incentive structures, which in turn affect their scalability, cost, durability and overall contribution to system-wide traceability:

1. **Commercial traceability solutions** are market-driven, vendor-operated systems that automate data capture and chain-of-custody accounting by integrating with enterprise systems, certification schemes and regulatory reporting workflows.
2. **Multi-stakeholder programmes** are broader initiatives designed to strengthen due diligence, risk mitigation, responsible sourcing and institutional capacity through partnerships. These programmes use traceability to enhance supply chain governance, including improved assurance mechanisms, stakeholder inclusion, regulatory alignment and evidence generation.
3. **Traceability support infrastructure** refers to the technical and governance foundations that enable traceability. By defining shared identifiers, data capture models, exchange protocols and verification services, this infrastructure translates regulatory requirements into interoperable data architectures that underpin traceability efforts.
4. **Research and development (R&D) initiatives** are time-bound or project-based research and analytical activities that generate evidence and insight, allowing to better understand supply chains, traceability gaps and compliance risks. They are typically supported through public funding and prioritise learning experimentation and evidence generation rather than operating persistent traceability systems or delivering commercial services.

The distinction between these categories is intended as an analytical device to highlight dominant organisational logics, rather than as a rigid classification of internally consistent system types. Within each category, there is significant diversity in design, governance and operational focus.

Among commercial traceability solutions, for instance, one can distinguish enterprise resource planning (ERP)-embedded solutions, commodity- or sector-specific platforms and standalone tools. These differ in cost structure, data depth, implementation effort and in their ability to support continuous, transaction-level traceability versus periodic compliance reporting.

Multi-stakeholder programmes range from due diligence systems and ASM formalisation pilots to certification-embedded corporate responsibility schemes. Their focus shapes enforcement capacity, geographic scope and institutional sustainability. Traceability support infrastructures also differ: some primarily codify legal requirements, while others provide the technical foundations for other systems to communicate and interoperate. Finally, R&D initiatives include scientific pilots and concepts as well as advanced risk analytics.

These four categories are analytically distinct yet structurally interdependent. Multi-stakeholder programmes rely on commercial traceability solutions to operationalise tracking and reporting and on support infrastructure to secure interoperability and regulatory recognition. Commercial solutions, in turn, depend on credible data and assurance processes generated by multi-stakeholder programmes. R&D initiatives cut across all three, feeding evidence and technical advances into programmes, commercial solutions and support infrastructures.

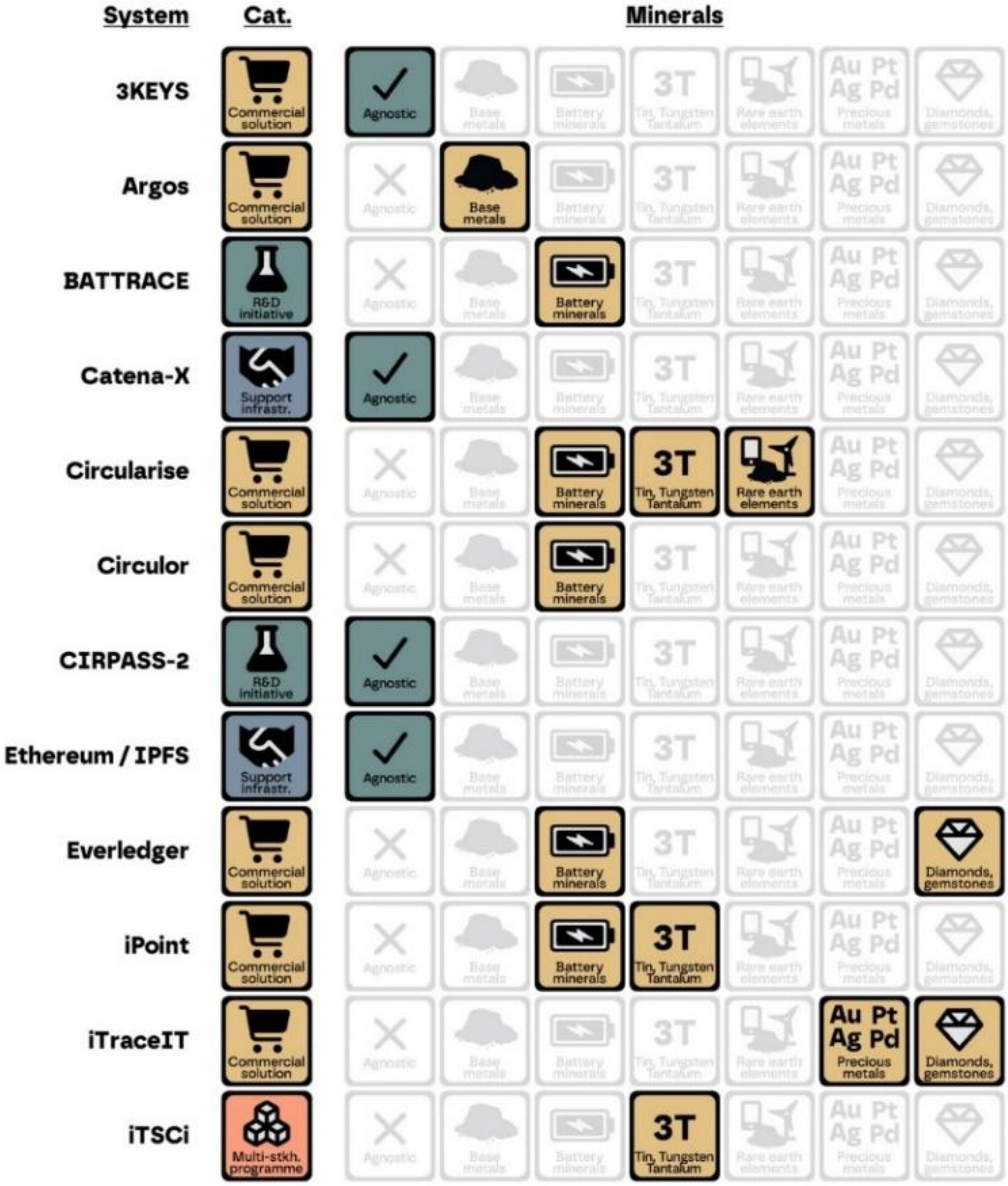
Table 2: Overview of Digital Traceability Systems

System name	Category	Main Focus
3KEYS	Commercial solution	Consulting and implementation provider for serialisation and track-and-trace projects supporting regulatory compliance and brand protection.
Argos	Commercial solution	Real-time digital monitoring for stock data and audit trails of bulk commodities using IoT sensors, drones and spatial scanning.
BATTRACE	R&D initiative	Research project on sustainable processing and traceability of battery metals and materials, exploring analytical methods for origin tracking and production optimisation.
Circularise	Commercial solution	Blockchain-based DPP platform providing mass balance traceability and tokenized sustainability certificates.
Circulor	Commercial solution	CRM and battery traceability system supporting due diligence and ESG risk management.
CIRPASS-2	R&D initiative	EU-funded multi-stakeholder innovation action building on CIRPASS pilot to scale real-world deployment and interoperability testing of DPPs aligned with ESPR.

Table 2: Overview of Digital Traceability Systems		
System name	**Category**	**Main Focus**
Catena-X	Support infrastructure	Industrial data space facilitating interoperable traceability and DPP frameworks for the automotive industry.
Everledger	Commercial solution	Blockchain platform providing traceability for high-value assets and a range of industries.
Ethereum / IPFS	Support infrastructure	Public decentralised blockchain combined with distributed file storage (IPFS), forming a general-purpose Web3 infrastructure used by some traceability applications.
iTraceIT	Commercial solution	Blockchain traceability platform capturing product origin, ownership, compliance documents and transformation history across complex supply chains.
iTSCi	Multi-stakeholder programme	Traceability for tin, tantalum and tungsten (3T) minerals due diligence in the African Great Lakes region.
MaDiTraCe	R&D initiative	EU-supported project developing digital and material traceability methods for CRM, integrating them into a prototype certification scheme.
Minespider	Commercial solution	Blockchain-based traceability platform for mineral supply chains, supporting multi-actor data sharing.
MineHub	Commercial solution	Digital platform for mining commodity transactions and supply chain collaboration, with integrated shipment tracking and provenance capabilities.
OPTEL	Commercial solution	Traceability and carbon reporting platform used by companies across multi-sector supply chains.
PeerLedger	Commercial solution	Blockchain-based traceability platform using shared ledgers to support ESG data exchange in supply chains.
RCS Trace	Commercial solution	Traceability platform for mineral supply chains, supporting chain-of-custody tracking and due diligence reporting, including implementation through programmes such as Better Mining.

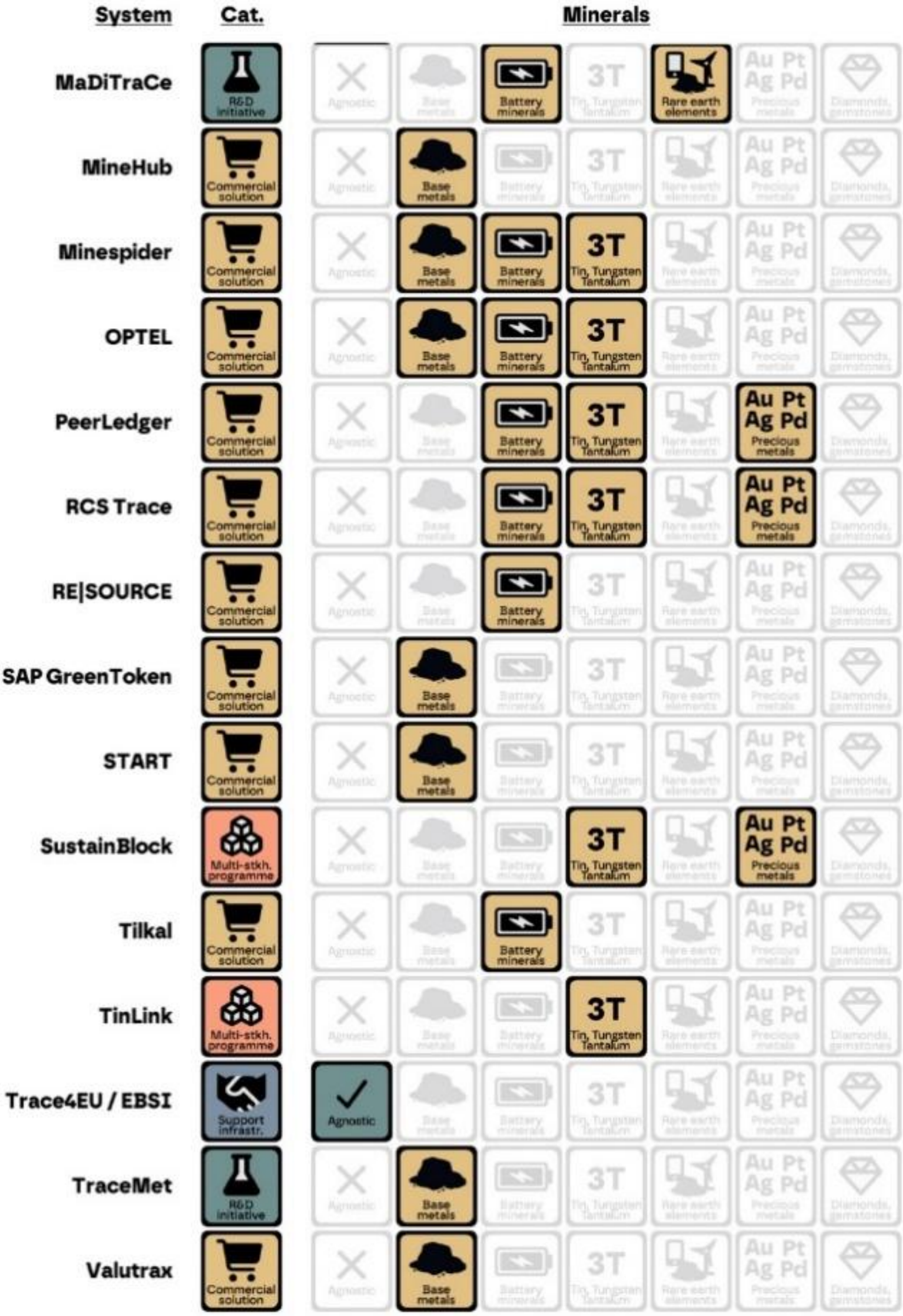
Table 2: Overview of Digital Traceability Systems

System name	Category	Main Focus
RE|SOURCE	Commercial solution	Supply chain traceability and ESG compliance platform for critical minerals and battery value chains.
SAP GreenToken	Commercial solution	Solution for mass-balance traceability and sustainability attribution in complex supply chains.
START (Rio Tinto)	Commercial solution	Customer-facing sustainability and traceability label for Rio Tinto products, providing shipment-level ESG metrics to support due diligence and reporting.
SustainBlock	Multi-stakeholder programme	Blockchain-enabled chain-of-custody pilot to strengthen due diligence, transparency and ASM inclusion in mineral supply chains.
Tilkal	Commercial solution	Blockchain-based multi-sector traceability platform combining supply chain data and analytics to support transparency, compliance and risk management.
TinLink	Multi-stakeholder programme	Blockchain-based project for enhanced traceability and due diligence in tin supply chains, integrating data and governance to support actor collaboration and transparency.
Trace4EU / EBSI	Support infrastructure	EU-led public blockchain infrastructure (EBSI) and associated Trace4EU pilots that explore traceability use and verifiable credentials for cross-border data exchange.
TraceMet	R&D initiative	Research and pilot initiative exploring technical and governance designs for metal traceability systems.
Valutrax (Anglo American)	Commercial solution	Proprietary blockchain-based traceability platform from Anglo American that tracks metals and minerals from mine to customer, providing product provenance and key ESG indicators.
iPoint	Commercial solution	Supply chain data management platform supporting traceability, due diligence and sustainability reporting.



System	Cat.	Minerals						
3KEYS	Commercial solution	✓ Agnostic						
Argos	Commercial solution		Base metals					
BATTRACE	R&D initiative			Battery minerals				
Catena-X	Support infrastr.	✓ Agnostic						
Circularise	Commercial solution			Battery minerals	3T Tin, Tungsten Tantalum	Rare earth elements		
Circulor	Commercial solution			Battery minerals				
CIRPASS-2	R&D initiative	✓ Agnostic						
Ethereum / IPFS	Support infrastr.	✓ Agnostic						
Everledger	Commercial solution			Battery minerals				Diamonds, gemstones
iPoint	Commercial solution			Battery minerals	3T Tin, Tungsten Tantalum			
iTraceIT	Commercial solution						Au Pt Ag Pd Precious metals	Diamonds, gemstones
iTSCi	Multi-stkh. programme				3T Tin, Tungsten Tantalum			

Graphic 1: Comparative overview of traceability systems according to functional category and mineral scope



System	Cat.	Minerals						
MaDiTraCe	R&D initiative			Battery minerals		Rare earth elements		
MineHub	Commercial solution		Base metals					
Minespider	Commercial solution		Base metals	Battery minerals	3T Tin, Tungsten Tantalum			
OPTEL	Commercial solution		Base metals	Battery minerals	3T Tin, Tungsten Tantalum			
PeerLedger	Commercial solution			Battery minerals	3T Tin, Tungsten Tantalum		Au Pt Ag Pd Precious metals	
RCS Trace	Commercial solution			Battery minerals	3T Tin, Tungsten Tantalum		Au Pt Ag Pd Precious metals	
RE|SOURCE	Commercial solution			Battery minerals				
SAP GreenToken	Commercial solution		Base metals					
START	Commercial solution		Base metals					
SustainBlock	Multi-stkh. programme				3T Tin, Tungsten Tantalum		Au Pt Ag Pd Precious metals	
Tilkal	Commercial solution			Battery minerals				
TinLink	Multi-stkh. programme				3T Tin, Tungsten Tantalum			
Trace4EU / EBSI	Support infrastr.	✓ Agnostic						
TraceMet	R&D initiative		Base metals					
Valutrax	Commercial solution		Base metals					

Graphic 1: Comparative overview of traceability systems according to functional category and mineral scope

3.2. Verification mechanisms for traceability

Traceability systems rely on different forms of verification that vary in strength and degree of independence. The table below summarises a commonly used cross-sector framework that distinguishes three tiers.

Tier 1 – **Proof of Intention** involves documentation that signals commitment to responsible sourcing. While necessary for governance and accountability, such documentation does not in itself verify material flows or origin.

Tier 2 – **Proof of Transaction** seeks to establish continuity of custody by linking physical materials to digital records across transactions. These systems aim to demonstrate that declared movements and transformations are internally consistent and procedurally controlled. They reduce opportunities for substitution or duplication but remain dependent on the integrity of data entry and physical–digital linkage.

Tier 3 – **Proof of Origin**, introduces independent material verification capable of confirming whether a material's intrinsic properties are consistent with claimed provenance. These methods provide external validation of administrative traceability systems but cannot substitute for continuous transaction-level tracking. Rather, they function as complementary audit or validation tools.

Table 3: Verification levels for traceability adapted from the OECD[29] based on the Nordic Innovation proof-of-concept study[30]

Verification level	Description	Examples
Tier 1: Proof of Intention	Basic documentation demonstrating compliance commitments.	Policies; Codes of Conduct; Supplier statements
Tier 2: Proof of Transaction	Chain of custody systems that track material flows through the supply chain.	CoC records; Blockchain-based tracking; Automated ID registration; Tagging and labelling systems; Geolocation; Time-stamping
Tier 3: Proof of Origin	Scientific or physical verification methods that confirm the origin or materials, beyond documentation and transactional records.	Isotopic and geochemical analysis; Physical fingerprinting*

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* Physical fingerprinting refers to determining the origin of a mineral sample by analysing its inherent characteristics. "Natural" fingerprinting relies on the material's intrinsic properties, such as geochemistry or mineralogy, while "artificial" fingerprinting introduces external markers, such as taggants or laser inscriptions, to certify origin.

Physical–Digital Linkage Mechanisms

Beyond formal chain-of-custody (CoC) documentation, Tier 2 verification relies on mechanisms that establish and maintain the link between physical materials and their associated digital records. These mechanisms vary in sophistication, cost and robustness and are best understood as complementary rather than mutually exclusive.

Barcodes and QR codes are widely used to establish physical–digital linkage, particularly for bag- or batch-level tracking in upstream and midstream contexts. Their low cost and ease of deployment make them attractive in environments with limited infrastructure, but they remain vulnerable to damage, duplication and intentional substitution.

Radio-frequency identification (RFID) tags enable a higher degree of automation by allowing items to be scanned without direct line-of-sight, which speeds up processing in logistics, warehousing and large industrial facilities. However, RFID systems require greater upfront investment and supporting infrastructure, which limits their applicability in remote, small-scale or low-formalisation settings.

These identification tools typically operate within **serialisation systems**, which assign a unique digital identifier to a physical object, batch or shipment and register it within a database. Serialisation allows materials to be distinguished from one another and tracked across transactions.

Event tracking and distributed ledger architectures

Event tracking refers to the structured recording of discrete supply chain actions – such as extraction, aggregation, processing, transformation, shipment or ownership transfer – each timestamped and linked to a specific identifier. Event data may be stored in centralised databases or distributed ledger systems, depending on governance design and interoperability requirements.

Blockchain-based systems do not replace identification or serialisation mechanisms. Rather, they provide a governance architecture for recording, validating and synchronising the chain-of-custody events that those mechanisms generate.

A **permissioned blockchain ledger** is a type of distributed ledger technology (DLT) in which only authorised participants may validate transactions, write data or access specific information[31]. Unlike public blockchains, participation is restricted to vetted actors and governance rules determine data visibility and validation authority. These systems use cryptographic techniques and consensus protocols to create a shared, append-only record of transactions. Under robust governance conditions, this design makes unilateral or retrospective alteration difficult, though not impossible.

Identifiers carried by barcodes, QR codes, RFID tags or digital twins can be tokenised on such ledgers (for example as batch- or product-level tokens) or linked via cryptographic hashes of off-chain records, creating a tamper-evident log that is shared among authorised participants[32].

While often described as tamperproof, ledger immutability ultimately depends on network design, governance arrangements and node integrity. Blockchain-based systems remain only as reliable as the data and physical–digital mappings entered into them.

In more formalised and downstream segments, traceability increasingly relies on **digital twins**, which represent materials, batches or products as persistent digital objects that accumulate provenance, processing, ESG and compliance data over time. Digital twins facilitate aggregation across tiers and support downstream reporting requirements such as DPPs. Their effectiveness, however, depends on the reliability of upstream identifiers and data flows. Where upstream linkage is weak or inconsistent, digital twins risk becoming representational constructs that document claims rather than faithfully reflecting material histories.

Artificial intelligence tools may support the analysis of large traceability datasets, including pattern detection and fraud identification, which can strengthen oversight functions. However, the application of these technologies within CRM traceability systems remains an emerging area and warrants further research to assess feasibility, governance implications and practical implementation considerations.

Complementary validation and control mechanisms

Spatial and temporal controls, such as geolocation, geofencing and time-stamping, are increasingly used to reinforce implementation, particularly in high-risk upstream contexts. By linking production, aggregation or transport events to defined geographic zones and time windows, these tools enable plausibility checks and the identification of red flags, such as material movements outside authorised areas. Their contribution to effective traceability depends less on technical precision than on institutional capacity to act on alerts and integrate them into risk-management and remediation processes.

To address the limitations of administrative chain-of-custody systems, some initiatives incorporate **scientific or material verification methods**, including geochemical, isotopic, mineralogical and DNA-based markers. These approaches are particularly relevant in midstream and downstream contexts where blending and transformation disrupt unit-level traceability and are often referred to as analytical proof of origin (APO).

One key example is BGR Analytical Fingerprint (AFP) tool used as an additional check on origin claims in 3T supply chains in the African Great Lakes region. While such methods can provide strong independent evidence of origin, detect anomalies and reduce the risk of fraud, they cannot replace continuous, transaction-level digital chain-of-custody tracking and should be understood as complementary validation tools. Their feasibility, cost and maturity vary significantly by mineral and context, making mineral-specific expertise and local supply chain knowledge essential for credible design and interpretation (see further section 6.3.).

Implementation considerations

Across all supply chain segments, technology choice should be understood as an implementation variable shaped by risk, scale, cost (see section 5.2.) and operational capacity, rather than as a linear progression toward ever more advanced solutions. Low-cost identifiers and human-centred controls remain indispensable in high-risk or low-formalisation contexts, while more automated, data-intensive mechanisms become viable only where organisational routines, infrastructure and incentives are already in place.

Therefore, effective traceability systems tend to combine multiple identification and verification mechanisms, aligning them with the specific operational realities of each stage of the supply chain.

3.3. Chain-of-custody models for material traceability

As set out in Section 2.2. on traceability in ESG standards, chain-of-custody (CoC) is used to describe traceability in two related senses: the documented trail of custody and transactions and the physical tracking of materials

the latter concerns how the material is tracked as it is produced, transformed, mixed, split and transferred. Four widely used material CoC models specify what mixing is permitted and what types of claims can be made (Kaikkonen et al., 2022):

1. **Identity preservation (IP)** requires that material from a certified production site remains physically separate from all other material throughout the supply chain, maintaining a direct link to the certified source and associated claims.
2. **Segregation** (sometimes referred to as “soft IP”) allows certified material from different approved sources to be mixed, while prohibiting any mixing with non-certified material; blending and transfers must be tracked and documented.
3. **Mass balance (MB)** allows certified and non-certified material to be mixed at one or more stages, with claims based on input–output accounting rules (i.e. the overall proportion of certified input), rather than a strict physical link.
4. **Certificate trading (book-and-claim)** decouples physical material flows from sustainability claims by issuing certificates for responsibly produced volumes at the point of origin. End users can purchase these certificates as credits, allowing them to claim that, even if the exact source of a given shipment is unknown, an equivalent volume has been produced under verified sustainable conditions.

Commercial traceability platforms can generally be configured to support different CoC rules depending on the mineral, the claim type and operational constraints. Multi-stakeholder programmes, by contrast, tend to apply a dominant CoC approach within a specific mineral, geography, or regulatory context.

Repeated blending and transformation across CRM supply chains render **identity preservation** from mine to final product operationally challenging. It is most viable where materials retain physical integrity and undergo limited downstream transformation. It is therefore usually confined to upstream stages or tightly controlled pilots, such as SustainBlock's pilot tungsten supply chain[33] in the African Great Lakes region and Rio Tinto's low-carbon can pilot[34], using QR codes to link consumers to footprint data for a defined aluminium batch.

Segregation is applied where approved material can be pooled while being kept separate from non-certified streams through controlled handling and recordkeeping. Upstream bag-and-tag programmes such as iTSCi (ITRI Tin Supply Chain Initiative) apply a segregation logic by aggregating tagged lots within a controlled chain of custody while seeking to exclude non-participating material[35].

Given the prevalence of blending and transformation, **mass balance** emerges as the dominant CoC model across the assessed approaches, particularly for processing-intensive and battery-related minerals. These include lithium, nickel, cobalt, manganese, graphite and copper, where intermediate products are routinely mixed, refined and recombined across multiple stages and facilities. **Certificate trading** appears mainly in limited pilot or experimental contexts, such as TraceMet's exploration of book-and-claim as an alternative to full physical track-and-trace[36].

4. Comparative mapping of digital traceability systems

This chapter synthesises the overarching patterns, emerging trends and structural gaps identified through the comparative assessment of 27 selected traceability approaches relevant to CRM value chains. These are presented in the matrix below. The matrix serves as a methodological instrument to support analysis and policy reflection and is not an evaluation or ranking of individual systems.

4.1. Scope, coverage and scaling logics

Scope and coverage depend on the respective traceability category.

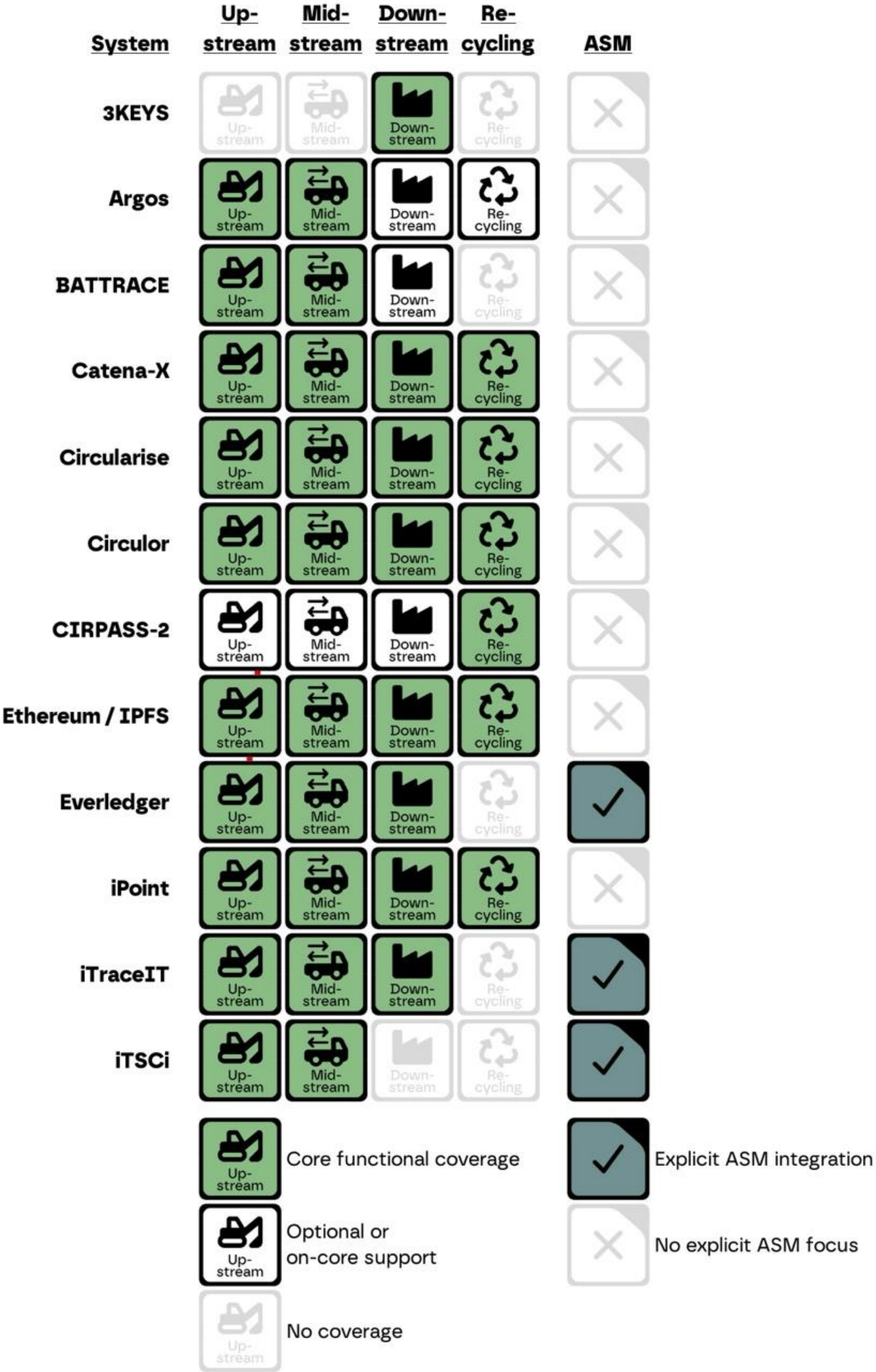
Commercial solutions are designed to operate across multiple minerals and sectors, integrate with corporate IT systems and serve industrial actors such as smelters, refiners, processors, traders and original equipment manufacturers (OEMs). Their strongest coverage is typically midstream and downstream, where processes are formalised and digital infrastructure is already in place. By contrast, producer-led systems—such as START by Rio Tinto and Valutrax by Anglo American—tend to cover upstream through downstream with a stronger focus on material CoC. These solutions generally scale horizontally by standardising workflows, automating data capture and reusing a common technical stack across actors and commodities. Illustrative examples include Circularise, which provides blockchain-based DPP infrastructure enabling mass balance traceability and tokenised sustainability certificates and MineHub, which supports digital commodity transactions and supply chain collaboration with integrated shipment tracking and provenance functionalities. Other platforms, such as Tilkal, combine blockchain-based traceability with configurable ESG data models and analytics, allowing firms to tailor transparency, compliance and risk management outputs across multiple sectors and regulatory contexts. Such models allow for low marginal costs at scale, making them suitable for broad deployment and compliance reporting across supply chains. However, they often lack the contextual depth, mandate or legitimacy to manage high-risk supply chains independently.

Multi-stakeholder programmes tend to be narrower in mineral and geographic focus but extend traceability into early-stage production. They typically scale vertically, going deep into specific supply chains, jurisdictions or production contexts, with high human involvement, limited automation and higher costs per unit of material traced. This depth enables multi-stakeholder programmes to operate in complex, high-risk and low-infrastructure situations – such as ASM and conflict-affected areas – but constrains their ability to expand quickly across sectors and geographies.

Support infrastructures are cross-cutting initiatives that do not target particular supply chains but provide shared identifiers, data models, interoperability rules and regulatory alignment that can be applied across minerals, sectors and jurisdictions. They scale through networks, amplifying the reach of both commercial platforms and multi-stakeholder programmes. Costs are largely fixed and upfront (design, standard-setting, coordination), with marginal expenses for additional users or transactions once the infrastructure is in place.

R&D initiatives focus on optimising traceability solutions or exploring new methodologies, prioritising innovation and proof of concept over large-scale implementation or rapid scaling across sectors. For example, CIRPASS-2, an EU-funded innovation action building on the earlier CIRPASS pilot, tests and refines DPP architectures aligned with the Ecodesign for Sustainable Products Regulation (ESPR), with an emphasis on interoperability and real-world deployment scenarios[37]. Similarly, BATTRACE explored analytical methods for tracing the origin of battery metals and improving sustainable processing, contributing methodological advances rather than operational traceability systems[38].

Finally, several initiatives position traceability as an enabler for **recycling and circular value chains**, as it carries information on end-of-life, reuse and recycled-content alongside provenance and ESG data Catena-X, an open industrial data space developed for the automotive industry, is working to facilitate data exchange for more efficient battery recycling and end-of-life processing[39]. Although circularity is an emerging area of traceability, it is still incomplete.



System	Up-stream	Mid-stream	Down-stream	Re-cycling	ASM
3KEYS	▫	▫	🟩	▫	✗
Argos	🟩	🟩	⬜	⬜	✗
BATTRACE	🟩	🟩	⬜	▫	✗
Catena-X	🟩	🟩	🟩	🟩	✗
Circularise	🟩	🟩	🟩	🟩	✗
Circulor	🟩	🟩	🟩	🟩	✗
CIRPASS-2	⬜	⬜	⬜	🟩	✗
Ethereum / IPFS	🟩	🟩	🟩	🟩	✗
Everledger	🟩	🟩	🟩	▫	✓
iPoint	🟩	🟩	🟩	🟩	✗
iTraceIT	🟩	🟩	🟩	▫	✓
iTSCi	🟩	🟩	▫	▫	✓

🟩 Core functional coverage

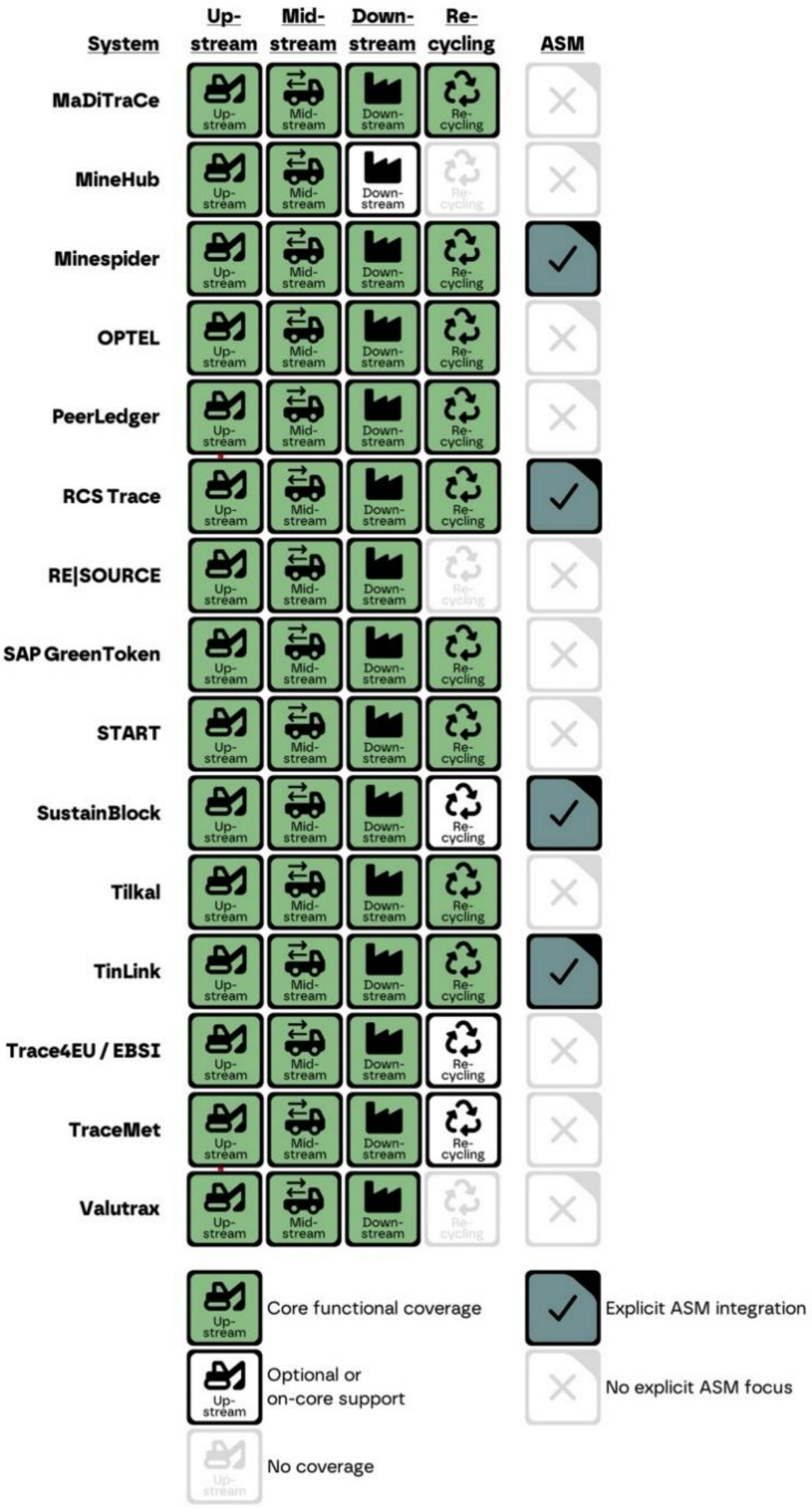
⬜ Optional or on-core support

▫ No coverage

✓ Explicit ASM integration

✗ No explicit ASM focus

Graphic 2: Comparative overview of traceability systems in relation to supply chain coverage and integration of ASM actors.



System	Up-stream	Mid-stream	Down-stream	Re-cycling	ASM
MaDiTraCe	🟩	🟩	🟩	🟩	✕
MineHub	🟩	🟩	☐	░	✕
Minespider	🟩	🟩	🟩	🟩	✓
OPTEL	🟩	🟩	🟩	🟩	✕
PeerLedger	🟩	🟩	🟩	🟩	✕
RCS Trace	🟩	🟩	🟩	🟩	✓
RE|SOURCE	🟩	🟩	🟩	░	✕
SAP GreenToken	🟩	🟩	🟩	🟩	✕
START	🟩	🟩	🟩	🟩	✕
SustainBlock	🟩	🟩	🟩	☐	✓
Tilkal	🟩	🟩	🟩	🟩	✕
TinLink	🟩	🟩	🟩	🟩	✓
Trace4EU / EBSI	🟩	🟩	🟩	☐	✕
TraceMet	🟩	🟩	🟩	☐	✕
Valutrax	🟩	🟩	🟩	░	✕

🟩 Core functional coverage

☐ Optional or on-core support

░ No coverage

✓ Explicit ASM integration

✕ No explicit ASM focus

Graphic 2: Comparative overview of traceability systems in relation to supply chain coverage and integration of ASM actors integration of ASM actors.

4.1. Governance and institutional arrangements

Governance arrangements span a spectrum from fully private to fully public, with multiple hybrid models in between. In particular across commercial solutions and multi-stakeholder programmes, governance is not only about who owns the system and data but about how core decisions are made in practice, namely who sets and updates rules, who defines participation requirements and how incidents and grievances are handled.

In **commercial solutions**, these functions are typically governed by the companies that develop and operate them. Roles, data access, responsibilities, liability and service continuity are primarily set through provider-defined operating rules and bilateral customer agreements. There is typically no government involvement, but the data generated is used for compliance reporting with applicable regulations. This model supports rapid iteration and scale, but it can also create dependencies on vendors and limit public oversight when key controls and decision rules sit with private operators. These solutions function as supporting tools, providing automated checks and analytics to make ESG claims verifiable, comparable and auditable across supply chains. Yet, when used in isolation exclusion can be reinforced as the underlying causes of the avoided risks are not being addressed.

Multi-stakeholder programmes generally rely on public–private governance arrangements, with decision-making shared across implementing partners and oversight bodies. Governments tend to play a more direct role in governance and enforcement. For instance, in a programme like iTSCi, public authorities participate in governance structures and take an active role in mine-site validation and the oversight of mineral batch tagging[40]. Similarly, the Better Mining programme developed by RCS Global Group (now part of SLR Consulting) combines continuous ESG risk monitoring, digital traceability and corrective-action planning at ASM sites to support responsible sourcing and due diligence[41]. TinLink also has a collaborative governance model, bringing together upstream producers, smelters, technology providers, supply chain intermediaries and civil society actors within a shared framework to enhance traceability and due diligence in tin supply chains[42]. Formalised roles for coordination, escalation and accountability help manage risks, remediation and inclusion on the ground. This shared governance can prevent de-risking is done through exclusion by enabling continued engagement in high-risk contexts.

The governance of **support infrastructures** focuses on rulemaking, maintenance and openness. These infrastructures often do not interact directly with individual supply chain actors, but their design choices determine what other systems can integrate with them. Governments are often involved in the rule- and framework-setting roles for these infrastructures, ensuring they comply with regulatory requirements. For example, initiatives like Trace4EU, built on the European Blockchain Services Infrastructure (EBSI), translate regulatory requirements into concrete technical rules that authorities can mandate or reference. These structures remain enabling layers. The actual implementation of traceability, including CoC logic, data capture, verification and risk management, continues to reside within dedicated traceability systems.

R&D initiatives operate under collaborative governance structures that include academic institutions, industry stakeholders and public funding bodies. Governance is centred on defining research priorities, methodologies and data sharing. Governments typically engage with R&D initiatives as funders, policy partners, or through strategic innovation programmes. A project like TraceMet was financed through a strategic innovation programme involving Swedish public bodies, helping develop pilot methods for tracking environmental performance and recycled content in metal supply chains[43]. Similarly, SUSMAGPRO, funded under the EU's Horizon 2020 research programme, aims to develop recycling technologies for rare earth magnets on a pilot scale[44]. While R&D initiatives do not enforce compliance directly, they generate evidence, prototypes, methodologies and insights that can inform the development of future regulatory frameworks, policy design and traceability standards.

4.2. Implementation and operationalisation

Implementation conditions for traceability systems vary across value chain segments. They are predominantly shaped by the point of implementation in the chain, the degree of formalisation and risk as well as the associated operational and data requirements, rather than by technology alone.

Upstream implementation (e.g., mine sites, first aggregation, local trade) depends on reliable routines to identify and track lots through weighing, recording and handover, regularly under variable connectivity and limited administrative capacity. **Midstream** implementation (e.g., processing, smelting/refining) is dominated by blending, transformation and inventory accounting, making continuous unit-level tracking difficult. **Downstream** implementation (e.g., manufacturing, OEMs, product passports) hinges on consistent data exchange and the ability to translate upstream records into product-facing disclosures and compliance reporting.

In **high-risk and low-formalisation contexts**, implementation is people- and process-intensive, relying on field staff, intermediaries, training, incident handling and sustained engagement with cooperatives and local authorities. In **more formalised environments**, implementation relies more on standard operating procedures, internal compliance workflows and automated checks. In such settings, secure serialisation solutions such as 3KEYS link physical components to digital records, while platforms such as iPoint integrate traceability and due diligence reporting into existing compliance workflows.

Where firms already use core business and production systems – such as ERP, production management and standard logistics and inventory tools – implementation can be accelerated through **integration into commercial platforms**. For example, Argos enables bulk commodity producers to embed independently verifiable stock data into existing inventory and ERP systems through IoT-based volumetric measurement, drone surveying and spatial scanning technologies. Where such systems are absent or unreliable, implementation relies on front-end data capture tools and sustained support to maintain data quality over time.

4.3. Data management

In traceability systems, **data quality** is primarily determined by governance and process. High-quality traceability data depends on disciplined operational routines, clear responsibilities and sustained oversight, particularly at upstream and transformation stages where risks of error and misreporting are highest. Automation and digital tools can improve consistency and scalability, but they do not eliminate the need for controls, audits and governance arrangements that determine the credibility of recorded data over time.

Data management arrangements vary across traceability systems. Commercial solutions typically rely on private cloud infrastructure and manage access through contractual arrangements and configurable system permissions. Multi-stakeholder programmes more often use donor-, government- or consortium-hosted infrastructure, with disclosure and control rules set through programme governance and operating procedures.

Traceability support infrastructures have emerged to address challenges of **data sovereignty**, including who controls traceability data, where it is stored, which laws apply and who can access or reuse it. Divergent requirements across producer, processing and consumer jurisdictions can constrain cross-border exchange. Privacy and cybersecurity concerns are key, as stakeholders seek assurance that sensitive data is protected against breaches and misuse. At the same time, these concerns can affect transparency and hinder data exchange by imposing stricter security standards[45]. Catena-X responds to these challenges through a decentralised data space, with its ‘10 Golden Rules’ setting baseline principles for participation and data exchange under a broader governance framework rather than a single vendor’s closed platform[46].

Hybrid hosting models are becoming increasingly common, combining centralised and decentralised infrastructure to enable secure, cross-border data exchange. For example, Minespider uses a public-permissioned blockchain that lets participants designate which data layers are public, consortium-only, or private, supporting both transparent traceability and controlled access across jurisdictions. Such approaches help balance national interests, commercial confidentiality and interoperability, which remains an ongoing challenge (see further section 5.2.).

5. Feasibility assessment of traceability approaches

This chapter assesses the feasibility of traceability solutions for CRM value chains, focusing on technical functionality, interoperability, economic viability and verification capacity.

5.1. Technical and infrastructure constraints in ASM contexts

Basic infrastructure remains a fundamental constraint on the feasibility of traceability systems, particularly in mining areas where gaps in connectivity, electricity and government oversight are common due to their remote locations. While such constraints can affect all mining operations, ASM faces additional structural challenges, including persistent informality, limited access to finance and lower education levels. These factors restrict access to hardware and reduce the capacity to engage with more complex digital systems.

In DRC's cobalt sector, for instance, artisanal mining often occurs in rural, harder-to-monitor areas with limited state presence. There are frequent reports that products from informal ASM are channelled into ostensibly formal supply chains at aggregation points, where material from multiple sources is combined. This significantly undermines provenance control[47].

Complex digital approaches risk excluding ASM actors if the operating realities of this subsector are overlooked. To onboard ASM into traceability systems, design approaches must prioritise accessibility and proportionality. From a technical perspective, this means ensuring actors can access basic technologies, such as mobile phones or simple barcode scanners, that do not require high-end connectivity or technical expertise. However, technology is just a small part of the solution. Feasibility depends less on sophisticated software features than on realistic data requirements, pragmatic operating models and alignment with existing institutional or commercial structures.

Many digital traceability approaches are **implicitly designed around established LSM**. In LSM contexts, mine sites are clearly defined, production is formally documented, and material flows follow established reporting channels. These characteristics provide a structured and standardised entry point for traceability. In many ASM settings, by contrast, production is dispersed across numerous localities. Informal aggregation and trading structures are prevalent and documentation at the point of extraction is often limited or unavailable. Therefore, it is usually not possible for traceability to begin at first extraction. Instead, it often starts at aggregation points, where material is consolidated and some degree of documentation becomes feasible.

This structural difference shapes both the scope and the limits of what traceability systems can credibly deliver in ASM contexts and may require the deliberate acceptance of managed uncertainty in system design. Institutional or commercial structures, such as cooperatives, mineral markets or buying centres, can serve as practical entry points (see further Section 6.2.). Ultimately, designing traceability for ASM requires adapting system architecture to existing production realities, rather than assuming the standardised conditions typical of LSM.

5.2. Interoperability challenges

CRM supply chains vary widely in extraction methods, trading structures, processing pathways and transport routes, making uniform mine-to-product tracking rarely realistic. In practice, companies rely on a patchwork of systems focused on specific regions, commodities, or segments of the value chain. This fragmentation increases costs, limits scalability and reduces the overall utility of traceability data.

Feasibility improves when systems concentrate data capture, verification and reconciliation at key **aggregation points**, such as cooperatives, buying stations, exporters and processing facilities. These locations, where large volumes converge, allow for standardised procedures. End-to-end traceability then depends on linking these verified checkpoints into a continuous data record, rather than applying the same traceability method at every step.

Because traceability rarely operates in a single system, **interoperability is the key enabler for scale** and the main antidote to fragmentation[48]. Approaches that rely on a single platform or closed architecture often struggle to expand. In practice, interoperability means enabling traceability data to transfer between systems, jurisdictions and product chains without repeated re-entry or reformatting. It does not hinge on a single technical feature, but on agreements and structures to collaborate and to align. It requires common identifiers for sites, companies and materials, shared data formats and transfer protocols, as well as technical connections, such as APIs (Application Programming Interface), that enable programmatic data exchange across platforms.

Interoperability is therefore as much a technical issue as a governance challenge shaped by several factors. First, it depends on the **ability of actors to collaborate** across organisational and geographic boundaries. Many traceability initiatives have focused on the ‘first mile’ of production but face greater difficulties midstream, where materials change ownership and physical form multiple times. As a result, traceability gains achieved upstream are often diluted once materials are blended or transformed further along the chain, frequently in other jurisdictions with greater processing capacity, such as China.

Second, **competitive dynamics** create barriers. Even where interoperability is technically feasible, firms may resist integration if it threatens perceived commercial advantage or requires disclosure of sensitive information. This can result in limited participation, selective reporting, or bare-minimum compliance. Some industry-led initiatives seek to coordinate traceability within controlled collaboration frameworks. For example, ReSource, jointly established by Glencore, CMOC Group (via IXM) and Eurasian Resources Group, provides a shared digital platform for traceability and ESG data exchange across battery and CRM value chains[49]. While such platforms can facilitate alignment among participating actors, they also illustrate how interoperability may develop within producer-led ecosystems rather than through fully open or neutral architectures.

Conversely, where such barriers are deliberately addressed and trust is built among actors with shared objectives, interoperability becomes a mutual benefit. For example, mid-2025, RMI and IRMA – which focus primarily on midstream and upstream standards respectively – signed an MoU to improve alignment for their shared members. By aligning tools and identifiers, exploring mutual recognition between mine- and processor-level standards, and piloting joint assessments, they seek to reduce duplication and strengthen due diligence[50].

Third, interoperability is increasingly shaped by **concerns over data sovereignty** and strategic autonomy. The EU frames data sovereignty as part of a broader geopolitical strategy. The European Strategy for Data (2020), along with the Data Governance Act (2022) and the Data Act (2023)[51], aims to strengthen economic efficiency while reducing dependence on foreign cloud providers and ensuring that data generated within the EU is governed in accordance with EU law.

As different powers pursue divergent approaches to data sovereignty and supply security,[52] traceability infrastructures themselves become politically salient. In the context of strategic competition over access to CRM, traceability data spaces may function not only as tools for transparency and risk management but also as potential sources of strategic intelligence or regulatory leverage. For example, within the framework of the International Conference on the Great Lakes Region (ICGLR) and its Regional Certification Mechanism for 3TG minerals, tensions between the DRC and Rwanda would have contributed to mistrust regarding access, storage and ownership of traceability data, complicating cross-border cooperation and data sharing.

Initiatives such as UNTP and Catena-X seek to reconcile transparency with confidentiality and security concerns by embedding data sovereignty principles within interoperable frameworks. Similarly, standard-setting and coordination forums – including ISO technical committees on CoC and digital ledgers, the (International Social and Environmental Accreditation and Labelling) Alliance’s work on sustainability and assurance systems, and the GBA’s Battery Passport – demonstrate how interoperability advances most effectively when anchored in clear regulatory requirements or strong commercial incentives. In their absence, voluntary collaboration tends to remain partial and uneven, insufficient to overcome structural barriers to interoperability.

5.3. Financial and economic feasibility

Despite technological advances, affordability and broader economic viability remain persistent constraints. Traceability systems are **resource- and energy-intensive**, requiring hardware, connectivity, staff time, training and ongoing data management. These inputs raise operational expenses, creating barriers to adoption, particularly in low-margin or infrastructure-constrained contexts. Effective system design therefore requires proportional, risk-based deployment to avoid unnecessary expenditure and prevent the exclusion of upstream or smaller actors.

Despite recognising the importance of traceability for compliance and due diligence, many downstream companies are **reluctant to cover full implementation costs**[53]. Studies show that battery manufacturers, for example, are often unwilling to finance traceability mechanisms without clear commercial value[54]. Even when firms accept recurring operating expenses, investment in scalable, shared infrastructure remains limited, and traceability is frequently pursued only in response to regulatory pressure or specific crises[55].

This contributes to a pattern in which high-profile issues – such as water scarcity in Chilean lithium or child labour in DRC cobalt – trigger short-term, reputationally driven traceability initiatives that are imposed on upstream actors with limited consideration of local conditions. Although such interventions may be well-intentioned, they often fail to support ongoing due diligence, risk mitigation or capacity building, and the information collected is not systematically used to improve practices over time[56].

Commercial traceability solutions are financed either through direct client commissioning or through recurring software-as-a-service (SaaS) licensing. In the **commissioning model**, large downstream companies (brands, OEMs, manufacturers) fund systems to manage regulatory exposure, reputational risk or due diligence obligations, imposing traceability requirements on suppliers. While this enables rapid deployment within defined supply chains, it often shifts compliance costs upstream and can limit interoperability, supplier choice and broader scalability.

The **SaaS model** offers a more standardised and potentially scalable configuration, enabling interconnection across value chain actors. Platforms such as OPTEL, which provides multi-sector traceability and carbon reporting, PeerLedger, which facilitates ESG data exchange through shared-ledger architecture, and SAP GreenToken, developed by SAP, which enables ERP-integrated mass balance traceability, illustrate this subscription-based approach. However, it depends on a sufficiently large paying user base to cover development and ongoing costs, including hosting cybersecurity, maintenance and user support. This creates selection effects. Smaller or lower-margin actors, particularly upstream operators and ASM, may be excluded or only selectively onboarded. At the same time, provider support costs do not scale down proportionally with client size, reducing incentives for inclusive system design.

These **cost dynamics also affect data quality**. When traceability is treated primarily as a compliance expense with no clear commercial value, participants may minimise effort, increasing the risk of incomplete documentation or weak verification. Some firms mitigate this by joining consortia or R&D initiatives to finance early-stage or higher-risk investments.

Public–private funding mechanisms have emerged to support inclusive deployment. For example, the European Partnership for Responsible Minerals (EPRM), which promotes responsible sourcing in conflict-affected and high-risk areas, has financed multi-stakeholder initiatives such as TinLink and SustainBlock to integrate ASM supply chains into traceability and due diligence frameworks. Such catalytic support can lower entry barriers and foster collaboration. However, scaling these models beyond the pilot phase remains a persistent challenge when long-term commercial incentives are weak.

More broadly, where traceability remains weakly linked to sustained commercial interests and value creation, uneven cost distribution and fragile business models constrain inclusivity, data reliability and long-term sustainability. Traceability therefore faces a **structural dilemma**. Regulators and downstream actors increasingly demand traceability, yet no actor is willing or able to absorb the full implementation costs. In the absence of a universally applicable business model, systems remain project-based, donor-funded, or confined to high-margin segments. This reinforces fragmentation and structural asymmetry, as many benefits of traceability accrue downstream while a significant share of implementation costs is incurred upstream.

There are, however, **practical pathways** to mitigate this structural dilemma. Mandating traceability more widely can help level the playing field and create clearer demand signals. In practice, adoption is driven less by ESG positioning than by commercial imperatives such as market access, client retention and risk management. Traceability becomes more viable when framed as compliance and risk infrastructure rather than as a consumer-facing premium.

5.4. Governance and verification capacity

Data governance arrangements determine whether traceability systems remain usable, trusted and legally operable over time. Beyond technical functionality, feasibility depends on clear rules governing confidentiality, accountability and verification.

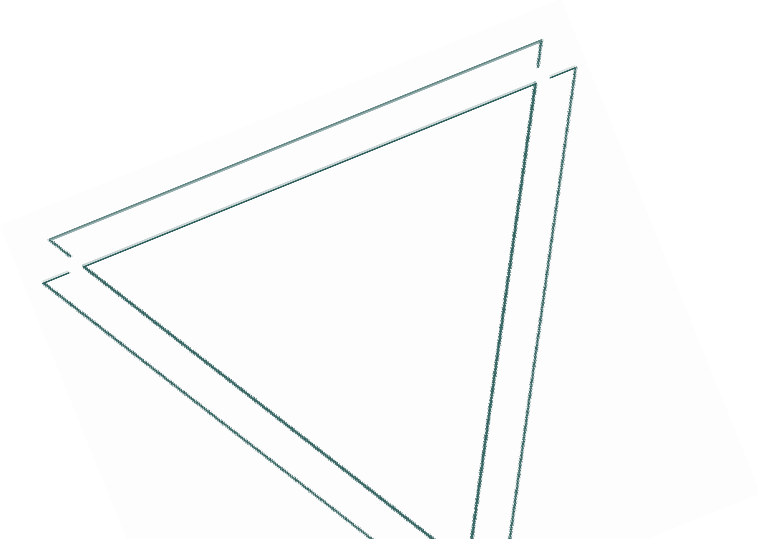
A central challenge lies in reconciling transparency requirements with **legitimate limits on data exposure**. One practical approach is to distinguish between asserted and attested information. Asserted data consists of self-declared information by supply chain actors, while attested data refers to claims verified by independent parties. Limiting disclosure to necessary attestations or digital conformity credentials can enable ESG verification without requiring full access to sensitive operational datasets.

Data quality, however, remains a structural constraint. Although digital ledgers can preserve records, they cannot guarantee the accuracy of information at the point of entry. Since data input almost always involves a human element, there is the risk of error, imprecision or manipulation. Effective verification through audits, conformity assessments or targeted technical checks therefore remains essential[57].

However, as traceability scales, **verification capacity** becomes a limiting factor. Data volumes can quickly exceed the ability of auditors or competent authorities to validate them. This renders systems fragile if they assume comprehensive, continuous verification. In practice, verification is already selective. Yet this selectivity often reflects capacity constraints rather than deliberate governance design.

Transparent decisions are required to address this, including which claims warrant independent verification, the level of assurance, the frequency of verification and the evidentiary basis. Prioritisation does not imply ranking ESG objectives but rather distinguishing between levels of risk, materiality and evidentiary need. Without clearer governance regarding verification priorities and cost allocation, expanding traceability demands risks outpacing available assurance capacity, undermining both data credibility and stakeholder participation.

Finally, governance models must adapt to increasingly interconnected traceability ecosystems. As cross-system data exchange expands, responsibility becomes more diffuse. Questions arise regarding **accountability** for errors, updates and liability once data moves across platforms. Feasibility therefore depends on governance mechanisms for data quality assurance, dispute resolution and lifecycle management of claims.



6. Impact assessment of advancing traceability

Building on the feasibility assessment of the previous chapter, this chapter examines the main positive and adverse impacts of more widespread implementation of traceability systems for CRM. It also considers how traceability systems might contribute to wider policy agendas in producer countries.

6.1. Supply chain characteristics and their implications for traceability

Before considering impacts from greater deployment of traceability systems, it is important to briefly highlight how structural factors in CRM supply chains can affect feasibility and impact the potential of traceability initiatives.

Non-linear supply chains and commodity characteristics

CRM supply chains are typically complex and non-linear. **Each CRM follows distinct extraction, trading, processing and transport pathways**, hence, traceability systems must be tailored rather than uniform. Lithium illustrates this challenge: hard-rock and brine extraction follow different pathways. Brine-based production involves extensive processing where material from multiple sources is often blended early, creating mixing points that reduce the ability to preserve discrete material identities and limiting the fit of standardised traceability models[58].

Cross-border, multi-jurisdictional supply chains are longer and involve more actors, making it harder to obtain granular data on production locations, local handling, transport and lower-tier suppliers. By contrast, where extraction and processing are geographically concentrated, provenance and material flows are easier to track. Platinum group metals (PGMs) illustrate this dynamic: production and refining are highly concentrated in Southern Africa and controlled by a small number of vertically integrated large international firms, resulting in shorter, less fragmented supply chains[59]. In such contexts, where provenance is largely known and governance structures are established, the proportionality of highly granular traceability becomes a key question, as additional cost and complexity may yield limited added value.

Traceability is generally more straightforward where extraction occurs through large-scale industrial operations with a narrower set of actors than in sectors where informal or illicit flows are more prevalent. Transport modalities also matter: bulk commodities such as copper are typically easier to track than high-value precious metals such as gold or diamonds that can be moved in small quantities and are therefore more vulnerable to smuggling[60]. Fixed offtake agreements can create relatively linear flows that are easier to document. Spot markets and multi-layer trading on the other hand can transfer ownership of materials multiple times, including to intermediaries with no physical link to the material, making traceability harder to implement[61] (see Box 5).

Around 60% of CRM are produced as by-products or co-products of other host metals[62], for example cobalt as a by-product of copper or gallium as a by-product of bauxite. When the primary incentive is to optimise host-metal production rather than the by-product, traceability expectations for CRM may not align with existing operational logics, limiting depth and granularity[63].

Box 4: The role of commodity traders

Commodity traders sit at key inflection points in mineral supply chains. They range from informal operators to large multinationals and commonly manage purchasing, transport, storage, blending and resale of ores, concentrates and secondary materials from multiple sources[64]. Large trading companies often track provenance internally for commercial and logistical reasons, with varying degrees of data granularity. While this information supports coordination and contract management, it is not equivalent to a formal traceability system[65]. In practice, many traders prioritise managing supply chain chokepoints over tracking every movement, since full shipment-level traceability can be costly and offers limited added value without clear regulatory signals or commercial demand.

Recycled materials

Global battery demand is projected to increase fourteen-fold by 2030[66] and post-consumer feedstocks are expected to grow as early electric vehicle (EV) and stationary batteries reach end of life. At the same time, regulations are introducing recycled-content requirements for batteries and other clean-energy technologies, which further increases the complexity of traceability. Under the EU Battery Regulation, manufacturers must document recycled content in new batteries, including whether recycled inputs come from manufacturing scrap or post-consumer waste, and have recycled-content claims independently verified. Most existing traceability systems are not designed to substantiate such claims.

Verification is difficult because recycled-material supply chains often obscure provenance. Feedstocks may come from mixed waste streams, pass through multiple handlers and lose original identifiers during dismantling and processing. These conditions break the link to the upstream origin and make recycled-content claims hard to confirm. At present, battery recycling is still dominated by manufacturing scrap, which is comparatively easy to document through controlled industrial processes. As post-consumer volumes rise after 2030, regulatory and traceability approaches will need to adapt to more complex, less controlled material flows.[67] Recycled graphite illustrates these challenges. While chemical analysis can identify the type of battery from which the material originated, it cannot reconstruct provenance or associated sustainability risks unless the material has been traced across its full life cycle.

These challenges do not render traceability impossible, but they **raise important questions about proportionality and purpose**. As recycled material availability increases and regulatory requirements expand, a central consideration is the degree of traceability granularity required to verify recycled-content claims, for what purpose, and in which cases less detailed verification may be sufficient. Clear definitions regarding the appropriate depth of traceability for recycled material remain under development.

In summary, **supply chain structure as well as system design impact performance.** Non-linear flows, multiple aggregation points, fragmented trading networks and commodity-specific features determine what can be captured at the point of data entry. Standardised architectures that do not reflect these conditions are likely to fail. In addition, **uniform data requirements may neglect material risks.** Applying the same data points across different CRM and contexts can overlook commodity- and location-specific risk factors, weakening the ability of traceability systems to capture what matters for performance and risk management.

6.2. Identifying positive impacts of implementing traceability

Traceability has multi-dimensional impacts. This section summarises key positive effects observed across CRM value chains. Strengthening mineral governance, supply chain transparency and revenue mobilisation

When embedded in national regulatory and fiscal systems, traceability-related tools can improve production oversight and revenue collection. By linking mine-level data, transport records and export declarations within integrated digital platforms, governments can more effectively verify royalties, monitor mineral flows and enforce compliance. This strengthens sector governance and enhances the credibility of state oversight and reporting.

Indonesia's SIMBARA platform integrates production, processing, transport, port and export data for nickel and tin, enabling real-time cross-checks of volumes and royalties across ministries. Government evaluations report that SIMBARA has prevented illegal mining worth Rp 3.47 trillion (~€177 million), increased state revenue by Rp 2.53 trillion (~€129 million) and recovered Rp 1.1 trillion (~€56 million) in outstanding receivables through automated cross-checks and oversight mechanisms. Officials also report improved supervision of the mining sector and reduced opportunities for illicit flows and revenue leakage[68].

Tanzania's establishment of mineral markets and buying centres in mining regions has increased transparency and reduced illicit trade by providing formal, recorded points of sale for small-scale miners. According to the Ministry of Minerals, mineral sales through these hubs increased from TZS 2.361 trillion (~€821 million) in 2021/22 to TZS 2.597 trillion (~€903 million) in 2023/24, supported by 43 mineral markets and 109 buying centres nationwide. These reforms helped to increase the contribution of small-scale mining to national mineral revenue from 4 to 40 percent.[69]

These examples show that even if such systems do not yet meet the end-to-end traceability expectations of downstream regulators, they constitute important steps toward greater transparency and provide a basis for future interoperability. Strengthening government capacity to digitise and operate such systems, and to ensure interoperability with international requirements, presents a significant development opportunity. When embedded in broader public sector digitalisation agendas, these tools can also reduce duplication, improve internal data accessibility, lower administrative costs and reinforce state oversight.

Enabling price differentiation and market incentives for responsible production

Traceability can enable product differentiation based on ESG performance and carbon footprint, allowing buyers to favour or reward better performers. For example, in 2024, the London Metal Exchange (LME) launched a physically settled spot contract for low-carbon nickel, giving buyers a concrete way to identify and reward lower-emission production[70]. The UK's *Vision 2035: Critical Minerals Strategy* similarly flags the potential for sustainability-linked contracts for other critical minerals,[71] providing policy support for traceability-enabled market mechanisms. Evidence shows that downstream manufacturers are already favouring materials with demonstrably lower embedded emissions or higher assurance levels, particularly ahead of EU Battery Regulation disclosure obligations. While formal premiums are not yet widespread, procurement preferences are beginning to shift toward verifiable ESG-performing inputs[72]. It is difficult to judge whether such trends are likely to grow and endure.

Price differentiation is still nascent and may initially benefit well-capitalised producers with strong data systems, risking wider disparities between supply chain actors. Credible verification and more equitable access to traceability tools will be essential if sustainability-linked markets are to advance responsible sourcing rather than entrench existing inequalities.

Strengthening upstream transparency, due diligence and anti-corruption efforts

Traceability generates data on origin, processing and transit routes, which can increase supply chain transparency, support corporate due diligence and help governments detect illicit or mis-declared shipments. Combined with governance and corruption-risk indicators, this information becomes a key input for identifying vulnerabilities and targeting mitigation measures. It may also support wider efforts to strengthen governance and transparency in the mining sector, e.g., the Extractive Industries Transparency

Initiative (EITI). Examples from producer countries illustrate the potential of this approach:

In the **DRC**, a **cobalt export-quota system** now links export authorisation to documented traceability and compliance. Exporters must meet administrative and compliance requirements, submit supporting documents such as historical production records and origin/quality attestations, and pre-pay a 10 per cent royalty within a defined timeframe. They must also obtain verification certificates and pass quota checks before shipment. Managed by ARESCOM (DRC's Authority for the Regulation and Control of Strategic Mineral Substances), the system is designed to tighten state control over cobalt flows, improve royalty collection and reduce opportunities for mis-declared or illicit exports[73].

In **Chile**, the digitisation of mining governance through platforms such as *Sistema de Exportaciones Mineras* (SEM 2.0), administered by the Chilean Copper Commission (COCHILCO), aims to enhance the visibility and credibility of export and revenue data[74]. By centralising information on production, permits and payments, these systems are intended not only to support market and compliance functions but also to strengthen domestic accountability and public confidence in how mineral resources are managed.

Together, these examples mark a shift toward using traceability-linked documentation as a condition for market participation and as a tool to bring previously informal or opaque flows under regulatory oversight. Yet fragmented datasets, opaque quota allocations and inconsistent enforcement can create new incentives for corruption and diversion, particularly where approvals lack transparency and discretionary decision-making widens the scope for informal payments or preferential treatment. This highlights both the potential and the limits of traceability-linked export controls in settings with uneven governance capacity and weak institutional safeguards.

The downstream value of state-led traceability or quota systems also depends on whether information can be shared beyond domestic authorities. If data remain siloed, traceability functions primarily as an internal market-control tool rather than enabling transparency and responsible sourcing along the full value chain. Ultimately, the contribution of such systems to trust and legitimacy depends on predictable implementation, robust data quality, credible institutions and data-sharing arrangements that protect national interests while providing the information needed by market and oversight actors.

Strengthening corporate risk management and strategy

Beyond regulatory compliance, traceability provides strategic value by improving visibility over operational, geopolitical and market risks. By linking material flows to specific regions, sites and suppliers, companies can identify chokepoints, anticipate disruptions and design more resilient procurement strategies. In this way, traceability acts both as an early-warning system and as a tool for managing reputational risk. For example, automotive manufacturers mapping their lithium supply chains identified a high dependence on Chile's Atacama Salt Flat, an area affected by water scarcity and indigenous rights concerns. This greater visibility over local risks helped motivate the creation of the Responsible Lithium Partnership, a multi-stakeholder initiative focused on more responsible resource management[75].

Where companies lack insight into conditions in sourcing regions, they are more exposed to disruption and public backlash. Integrating traceability-derived information into corporate risk assessments enables firms to anticipate emerging pressures, adjust procurement and engagement strategies, and better align supply security with responsible sourcing objectives.

6.3. Identifying adverse impacts of traceability implementation

Beyond their benefits, traceability measures can also have adverse distributional, governance and sustainability impacts. This section sets out the main ways these risks can materialise.

High costs, excluding upstream actors and encouraging illicit mineral flows

Traceability and due diligence often create significant financial and administrative costs that are pushed upstream to miners, traders and exporters, who typically operate on thin margins. Audit and certification fees, levies, site assessments and onboarding to digital platforms are frequently billed to upstream actors and rarely reflected in the prices they receive[76]. Because most value is added further downstream in processing and manufacturing, upstream actors have limited scope to recover these costs, especially when companies rely on proprietary or duplicative audit schemes instead of shared standards.

For small operators, delays linked to verification and documentation can mean lost sales or cash-flow crises, making formal compliance unattractive. In some contexts, this has encouraged disengagement from formal supply chains and, at the extreme, a shift towards informal trade and smuggling channels that sit outside due diligence altogether[77]. These dynamics undermine the governance aims that traceability is intended to support.

Disengagement from high-risk regions instead of improved due diligence

In practice, digital traceability is sometimes treated as a box-ticking exercise rather than as an input to risk-based due diligence. Companies may rely on chain-of-custody records and documentation as de facto proof of "clean" supply instead of investing in deeper on-the-ground assessment, especially in conflict-affected and high-risk areas (CAHRAs). The experience around Dodd–Frank Section 1502 is instructive: although the law did not prohibit sourcing from eastern DRC, its disclosure requirement was widely interpreted as a signal to avoid the region.

Many firms exited, instead of implementing robust due diligence, contributing to a de facto embargo that reduced formal trade opportunities for artisanal miners, harmed local livelihoods and did little to address underlying conflict dynamics[78]. It also shifted complex governance and oversight expectations onto private actors, creating burdens that upstream producers, especially vulnerable producers, continue to face[79]. This illustrates how provenance data, if misused or misunderstood, can trigger risk avoidance rather than responsible risk management. A similar dynamic could emerge if digital traceability is treated as a standalone compliance objective, rather than as one tool within the wider responsible sourcing toolbox.

Increased energy requirements and CO2 emissions

Digital traceability systems depend on hardware, connectivity, data centres and in some cases, energy-intensive transaction validation. Blockchain-based systems are of particular concern where they rely on high-energy consensus mechanisms, which can be among the most electricity-intensive digital technologies globally[80]. As a result, digital traceability can contribute to climate change impacts that run counter to the sustainability goals these systems are intended to advance.

Climate impacts of blockchain-based systems vary considerably depending on their technical design. Alternative architectures can materially lower the footprint of digital traceability applications built on similar technologies. For example, in 2022, Ethereum replaced proof-of-work (PoW) with a proof-of-stake (PoS) mechanism, reducing its energy consumption by an estimated 99 percent[81]. PoW validates transactions through energy-intensive computing (“mining”). PoS validates transactions by requiring validators to lock up (“stake”) assets instead of using large amounts of computing power.

Selecting proportionate, energy-efficient digital architectures is essential to ensure traceability systems do not introduce sustainability impacts that outweigh their benefits. The energy consumption of blockchain-based systems is leading to calls for regulatory interventions to mitigate adverse climate impacts[82]. While the energy intensity of large blockchain networks has been widely studied, the likely negative footprint of blockchain-based traceability applications, particularly if deployed at scale, and its relationship to the potential sustainability benefits such systems may support, has been less systematically assessed and would benefit from further analysis.

Narrow mineral coverage and blind spots

Many traceability efforts focus on a small group of high-profile critical minerals (such as cobalt, lithium or rare earths) and pay limited attention to by-products or co-products. This can create structural blind spots. For example, gallium[†]is produced almost entirely as a by-product of bauxite or sphalerite[83]. In the United States, for example, much of the attention to critical minerals has typically focused on battery manufacturing, with comparatively fewer resources directed towards other important minerals such as gallium[84]. In Guinea, most bauxite is exported in raw form: gallium is neither recovered domestically nor captured by traceability systems centred on bauxite exports. Conservative estimates suggest that bauxite mined in 2024 contained approximately 2,000 tonnes of recoverable gallium, far exceeding global annual production[85] of approximately 760 tonnes,[86] but these are likely not captured in traceability system data even though it is associated with the same upstream environmental and social impacts.

Such an imbalance can result in some by-product minerals receiving less policy attention, leaving governments and industry less well-prepared to anticipate or manage potential supply disruptions and ESG risks that traceability could help identify.

Similarly, when traceability focuses only on one extraction route (for instance, hard-rock lithium) and ignores others (such as brines or recycled sources), downstream buyers lose visibility over significant risk exposures, and producer countries miss opportunities to govern and benefit from the full range of minerals in their portfolio. As a result, traceability can reinforce uneven transparency across commodities and routes, offering detailed oversight for a few high-profile minerals while leaving other, equally consequential flows largely invisible.

6.4. Linking traceability to wider policy priorities in producer countries

Traceability in producer-country contexts is shaped by the way it aligns with broader national development priorities. Rather than functioning as a standalone compliance tool, it is most viable when **embedded within state-led mineral governance systems** that strengthen oversight, support revenue mobilisation, and align with industrial policy objectives.

In this configuration, traceability builds on existing administrative functions. Governments already act as primary custodians of core traceability inputs, including licensing registers, production declarations, transport documentation, and export records. Where these systems are formalised, digitised, and made interoperable, they can generate reliable, state-validated data that supports both domestic governance and downstream transparency requirements. Traceability can thus be understood not as a separate system, but as an extension of existing public authority and data infrastructures.

[†] Gallium is mainly used in products that contain microelectronic components, as well as in the manufacture of optoelectronic devices and semiconductors, among other applications.

Multiple producer country governments are strengthening **domestic data and administrative systems** to improve oversight of production, processing, and trade, enhance fiscal recovery, and support industrial policy objectives such as value addition and broader digitisation agendas. These efforts are significant because they establish the foundational data infrastructure upon which traceability systems depend. The following examples illustrate how such infrastructure has been mobilised in practice.

Indonesia's SIMBARA system was originally developed for coal and later expanded to nickel and tin. It links mine, smelter, transport and port data, enabling authorities to verify volumes, monitor mineral movements and reduce revenue leakage[87]. It functions primarily as a digital information and monitoring tool for tax enforcement and regulatory control and forms part of a broader digital public infrastructure agenda. The government is now undertaking an international policy mapping exercise to integrate wider sustainability objectives into the platform and improve interoperability across ministries, although capacity and resources remain limited.

In **Chile**, the **SEM 2.0** is a digital mining export system used to oversee copper and copper by-product exports. Exporters must register key contract terms and submit integrated value declarations for each shipment. By comparing these declarations with customs data and international price benchmarks, SEM 2.0 helps authorities monitor transactions, detect mispricing and limit revenue leakage. Automated checks, mandatory fields and sanctions emphasise its compliance and enforcement role[88]. While SEM 2.0 generates granular export information, broader ESG parameters are handled through separate systems. Achieving more integrated traceability outcomes therefore depends on coordination across platforms and sufficient institutional capacity.

Guinea shows how digitised systems could extend traceability principles to the management of mining revenues. Under the Mining Code, the **Local Economic Development Fund** (FODEL) is funded by company payments equal to 0.5 percent of turnover for bauxite and iron projects and 1 percent for other minerals, transferred to subnational authorities in communes directly affected by mining operations[89]. In response to concerns about transparency, civil society organisations have developed "Transparency FODEL", a digital platform intended to ensure the traceability of FODEL revenues and their use at the local level[90]. Complementing this, the National Fund for Local Development (FNDL) is financed by 15 percent of mining revenues and managed by the National Agency for Local Government Financing (ANAFIC), which is progressively digitising budget and accounting systems in communes to improve investment planning, the traceability of financial flows and reporting[91].

The link between **value addition agendas** and traceability is also significant. Advancing traceability without considering vertical integration and in-country processing, risks missing structural shifts in producer countries. Local processing can shorten supply chains, concentrate material flows and make oversight more feasible, while increasing incentives for governments to strengthen mineral governance and align traceability with development objectives.

At the same time, value addition requires investment to address capacity constraints, offering an entry point for embedding traceability and improving upstream visibility. To date, however, the systematic integration of traceability into value addition strategies remains limited and warrants further examination. This consideration aligns with the need to strengthen the business case for traceability discussed in the previous section. Partnership models that move beyond transactional supply chains, integrating standards, traceability systems, and governance support, may help align security-of-supply objectives with producer-country priorities.

Despite these opportunities, **important constraints remain**. In many jurisdictions, administrative systems are still paper-based, fragmented across institutions, or operationally inaccessible. This limits effective oversight and reduces the reliability of data available for traceability purposes, while creating space for misreporting and fraud.

Public-sector digitisation can help address these constraints by improving the availability and usability of official mining data, while lowering the marginal cost of meeting external market requirements. At the same time, the growing role of private actors in supporting such efforts introduces new governance considerations. For example, KoBold Metals is cooperating with authorities in the DRC to digitise geological and mining data as part of broader efforts to strengthen sector governance[92]. While such initiatives can enhance data availability and support investment, they also raise questions regarding data ownership, access and the role of private actors in shaping public data infrastructures. Although not designed as traceability systems, these efforts illustrate how foundational data improvements can support the development of credible traceability mechanisms.

International initiatives such as the UNTP (see Box 3) seek to establish shared data models, interoperability principles and enabling infrastructure to support traceability across jurisdictions and supply chains. For producer countries, such frameworks carry strategic implications. They provide an opportunity to articulate the development use case for traceability and to define how national governance systems can generate and interface with internationally recognised data structures. However, if frameworks, standards and downstream regulations are designed without structured input from producer-country stakeholders, they risk being perceived as mainly adding administrative pressure[93]. They may also fail to leverage emerging national systems that are capable of generating traceability-relevant outputs as an ancillary function of their primary governance agenda.

Systematic support is therefore needed to enable producer-country governments to engage with and implement international traceability frameworks. This includes **strengthening participation in framework design**, clarifying the domestic development rationale for adoption and directing investment towards the infrastructural conditions required for effective implementation. Traceability requirements introduced without parallel investment in these enabling conditions are unlikely to function effectively.

Supporting interventions, including public-sector digitisation and improvements in energy and telecommunications infrastructure, can establish the practical foundations for traceability systems to operate at scale. Such efforts also align with broader policy agendas, including the EU's green and digital transition, creating opportunities for greater policy coherence and development cooperation.

Box 5: Costs, incentives and uptake of traceability in producer countries

Upstream actors already shoulder a disproportionate share of due diligence and traceability costs. These investments are easier to justify when traceability is embedded in broader efforts to strengthen producer-country mineral governance and oversight. Several emerging Royalty Management Systems demonstrate this approach. Zambia's Mineral Output Statistical Evaluation System (MOSES), developed by the Zambia Revenue Authority with UNCTAD, is used to monitor production and export permits, improve revenue collection and enhance transparency in the mining sector[94]. Similar Royalty Management Systems are being developed in Kenya and Uganda, while the People's Republic of China is integrating traceability into its Rare Earth Management Regulations, including through the China Battery ID System[95]. Positioning traceability within such state-led digital architectures strengthens the cost–benefit case for adoption by ensuring that resources invested in these tools generate governance and operational value, rather than remaining isolated compliance costs.

Framing traceability within this wider business case also aligns with stakeholder calls and initiatives such as the World Economic Forum, which presents digital traceability as a strategic enabler of sustainability, circularity and supply chain resilience. At the same time, as value chain efficiencies improve, traceability costs are often passed along the chain, ultimately reaching end products and, in some cases, consumers[96]. A key challenge for producer countries is therefore to promote adoption and integration into supply chain management while avoiding cost distributions that further disadvantage already constrained upstream actors.

7. Recommendations for international cooperation

7.1. Promote principles for meaningful CRM traceability

- **Treat traceability as a tool for due diligence, not as a substitute for it.** Ensure traceability data is explicitly linked to risk assessment, mitigation plans and monitoring systems rather than treated as a standalone compliance output.
- **Use traceability to enable continued engagement in high-risk contexts.** Design systems that generate actionable risk information to support mitigation and remediation, rather than incentivising disengagement or exclusion.
- **Prioritise progressive improvement over absolute certainty.** Focus traceability requirements on decision-relevant ESG indicators and material risks, avoiding requirements for full granular coverage where institutional capacity is limited.
- **Promote complementarity and interoperability rather than one-size-fits-all solutions.** Support traceability models tailored to mineral characteristics, risk exposure and actor capacity, while requiring shared identifiers and data formats to prevent system fragmentation.
- **Embed robust verification and governance safeguards into system design.** Specify which claims require independent assurance, at what level and frequency, to balance credibility and cost.
- **Institutionalise cross-sector learning mechanisms.** Establish structured exchanges between mineral sectors and producer regions (e.g., through working groups or joint pilots) to accelerate adaptation of proven models.
- **Embed producer-country co-ownership in governance structures.** Include formal decision-making roles for producer-country authorities in standard-setting, system oversight and evaluation.

7.2. Promote interoperability and coordinated data-sharing frameworks

What international cooperation can do:

- **Facilitate alignment of identifiers and core data fields across systems**, including mine identifiers, shipment references and ESG claim categories, to reduce duplication and inconsistent reporting.
- **Support operational pilots of cross-system data exchange**, particularly under frameworks such as the UNTP, to demonstrate practical interoperability across selected CRM value chains.
- **Raise awareness of the differentiated roles, mandates and governance models of traceability systems**, ensuring that regulators, industry actors and producer-country stakeholders align expectations

and decision-making with each system's scope and function.

- **Invest in capacity building and operational literacy among producer-country authorities, midstream firms and downstream actors**, so that decentralised data-sharing models are understood, trusted and effectively implemented.
- **Strengthen midstream supply chain engagement** by mapping key midstream actors, challenges, and opportunities, and using this analysis to guide engagement. This should help ensure that traceability gains achieved upstream are preserved as materials are further processed and blended, including in jurisdictions with higher refining capacity such as China.

What international cooperation can promote:

- **Regulatory alignment** across EU and other downstream jurisdictions on core traceability data fields and minimum ESG disclosure categories.
- **Cross-recognition of standards**, enabling verified information to be reused across systems rather than repeatedly re-entered or reassessed
- **Secure data-sharing architectures that separate independently verified ESG attestations from commercially sensitive operational data**, ensuring trust without compromising confidentiality.
- **Inclusive and iterative design processes**, ensuring that interoperability frameworks are co-developed with producer-country governments, industry and civil society rather than introduced after core parameters are fixed.

7.3. Aligning traceability with producer country agendas

What international cooperation can do:

- **Align traceability initiatives with national development priorities** (e.g., value addition strategies, revenue mobilisation reforms and digitalisation agendas), thereby creating tangible incentives for producer-country engagement with downstream traceability requirements.
- **Support country-specific roadmaps** linking traceability to revenue mobilisation, industrial policy and digital governance strategies, to improve production and export data integrity, reduce leakages, enhance revenue capture and strengthen regulatory oversight.
- **Ensure meaningful participation of producer-country governments, industry and civil society in traceability design and standard-setting**, including through structured consultations (e.g., under frameworks such as the UNTP) and formal feedback mechanisms shaping feasibility assessments and phased implementation.

- **Explore the co-development of a producer-country-focused implementation module** under international frameworks such as the UNTP, operationalising interoperability with state-administered mineral governance systems. Building on precedents such as sector-specific derivatives (e.g., RBTP under the RBA), such a module could provide practical guidance for aligning national data systems with international traceability standards.
- **Support the development of national data governance frameworks** defining how traceability-relevant information is collected, verified, stored, shared and protected, while ensuring interoperability respects domestic regulatory structures, commercial sensitivities and national interests. This may include:
    - **Progressive implementation pathways** that strengthen foundational governance systems before scaling digitalisation.
    - **Gradual digitisation of national mineral information and core administrative systems** (e.g., cadastres, export licensing, royalty and tax systems) to embed traceability-relevant data within public infrastructure.
    - **Targeted research and innovation to render state-administered mineral data interoperable** through standardised formats compatible with international frameworks, while safeguarding sensitive information and preserving government custodianship.

What international cooperation can promote:

- **Recognition of national systems as primary and authoritative data sources** within international traceability frameworks.
- **Investment in technology-neutral enabling infrastructure** (e.g., connectivity, energy access, data storage and governance capacities) as a foundation for scalable and inclusive traceability implementation.
- **Structured exchange of best practices and technology transfer** to strengthen global traceability systems and enable wider participation by developing producer countries.

7.4. Enable inclusive and proportionate traceability in ASM contexts

What international cooperation can do:

- **Leverage instruments such as Global Gateway and related initiatives** to mobilise investment in energy and telecommunications infrastructure in ASM-intensive mining regions.
- **Support the design and implementation of pragmatic operating conditions** that allow for managed uncertainty and progressive improvement rather than rigid binary pass–fail models. Initial

implementation should focus on realistic entry points – such as cooperatives, traders or buying centres – with traceability extended upstream over time as capacity and oversight improve.
- **Support the development of differentiated traceability approaches for artisanal mining (AM), small-scale mining (SSM) and LSM,** ensuring proportional requirements aligned with operational capacity, risk profiles and level of formalisation.
- **Assist producer governments in strengthening or establishing aggregation and trading structures** (e.g. cooperatives, mineral markets, buying centres) to integrate ASM material into formal markets. These structures can provide market access, reduce incentives for illicit trade, improve oversight of volumes and payments, and serve as practical traceability nodes where extraction-level documentation is unavailable.
- **Address the evidence gap through structured research and pilot evaluations** assessing the operational feasibility, socio-economic impacts and governance implications of ASM-inclusive traceability models across different country contexts.

What international cooperation can promote:

- **Incorporation of proportionality principles into international standards and downstream regulatory frameworks**, explicitly recognising ASM realities and capacity constraints.
- **Structured dialogue between producer-country regulators, ASM representatives and downstream actors** to co-design inclusion pathways rather than imposing uniform compliance expectations.
- **Alignment of traceability requirements with technical assistance and infrastructure investment**, preventing exclusion through cost or technological barriers.
- **Capacity development for managed uncertainty approaches**, prioritising decision-relevant ESG information at aggregation points rather than requiring granular extraction-level certainty in all contexts.

7.5. Ensure fair and sustainable financing of traceability

What international cooperation can do:

- **Support predictable regulatory timelines and compliance signals from the German government and EU partners**, reducing investment uncertainty and enabling long-term planning by producer countries and firms.
- **Support risk-based prioritisation of traceability investments**, concentrating resources on areas of highest material risk rather than attempting universal, mine-to-product coverage across all supply chains.
- **Provide catalytic, time-bound support for early-stage design,**

piloting and capacity building, particularly in ASM and low-infrastructure contexts, while embedding clear transition strategies to avoid long-term donor dependency.

- **Support the development of a proportional, risk-based cost-sharing norm**, aligning financial contributions with both capacity and benefit distribution across the value chain, and recognising the asymmetric capture of compliance and reputational gains.
- **Support the design of proportionate verification architectures**, clearly defining which claims require independent assurance, at what level and frequency, to prevent assurance bottlenecks and escalating costs.
- **Support continued research, development and evaluation of geo-based fingerprinting technologies**, ensuring that large-scale adoption is evidence-based and economically viable.

What international cooperation can promote:

- **Hybrid public–private financing models** combining regulatory mandates, private investment and targeted donor support to equitably distribute upstream costs through shared infrastructure funds, levies or premium mechanisms.
- **Greater coordination among European development agencies and industry platforms**, including through mechanisms such as the EPRM, to reduce duplication and fragmented funding streams.
- **Transparent dialogue on cost allocation**, openly addressing “who pays” and aligning contributions with both capacity and benefit capture along CRM value chains.
- **Incentive mechanisms** (e.g., tax incentives, credits, or regulatory recognition for sourcing from designated jurisdictions) to reward companies that maintain engagement in high-risk areas while meeting due diligence standards.
- **Reframing traceability as shared operational infrastructure**, underpinning inventory management, supply chain visibility and resilience, rather than as a discretionary compliance add-on

8. Conclusions

Traceability is becoming central to responsible critical mineral value chains. The expansion of due diligence and ESG expectations, concerns over long-term security of supply and rapid digital innovation have elevated traceability from a niche compliance mechanism to a structural feature of emerging supply chain governance. Against this backdrop, understanding both the potential and the limitations of digital traceability systems is essential.

Technological advances now make it feasible to track minerals across extraction, processing, manufacturing, use and recycling. Yet technology alone does not ensure responsible sourcing. Digital systems can collect and transmit large volumes of data, but their value depends on interpretation, risk assessment, mitigation and monitoring. Traceability strengthens due diligence only when information generated is acted on.

Data integrity remains a structural constraint. While digital systems preserve records, they cannot guarantee accuracy at the point of entry. Human judgment remains involved and therefore risks of error or manipulation persist, making independent verification indispensable.

Risk prioritisation should be guided by materiality and by realistic verification capacity. Traceability must focus on locally salient and ESG-relevant risks rather than attempting comprehensive coverage or privileging what is easily quantifiable. As data volumes grow, the capacity to provide assurance becomes constrained. This requires clear decisions about which claims merit independent verification, at what level and frequency. Without such governance, expanded traceability may narrow due diligence or erode trust instead of reinforcing it.

Long-term scalability depends on reframing traceability not as a discretionary compliance add-on, but as shared operational infrastructure underpinning inventory management, supply chain visibility and resilience. Embedding traceability within core business systems can reduce marginal compliance burdens and align responsible sourcing objectives with commercial incentives.

When treated as a standalone compliance instrument, traceability risks reinforcing existing power asymmetries, incentivising disengagement from higher-risk regions and excluding vulnerable actors, particularly in the ASM sector. Conversely, when integrated into meaningful due diligence processes, traceability holds strategic potential beyond compliance. Realising that potential depends on addressing a set of structural constraints that currently limit adoption, scalability and effectiveness

8.1. Managing fragmentation: the centrality of interoperability

Fragmentation in regulations and standards has produced overlapping and sometimes inconsistent traceability requirements. At the same time, CRM supply chains differ significantly in structure, extraction methods, trading arrangements, processing techniques and end uses, resulting in divergent traceability needs and implementation barriers. The outcome is a fragmented ecosystem of systems often concentrated in specific regions, commodities, or value chain segments. This patchwork limits economies of scale, increases compliance costs and constrains data usability and comparability.

Reducing fragmentation requires clarifying the roles, governance models and mandates of different traceability systems. This report has mapped and categorised existing initiatives to distinguish their scope, governance arrangements, implementation approaches, data management models and scalability constraints. Clarifying these differences is essential for effective coordination and coherent policy support. Without such differentiation, expectations become misaligned and fragmentation is reinforced.

Because uniform mine-to-product tracking across all supply chains is rarely realistic, scalability depends fundamentally on interoperability. Data must be able to move across systems, companies and jurisdictions without repeated entry or loss of integrity. Interoperability requires alignment on identifiers, shared data formats, cross-recognition of standards and secure exchange protocols. It is therefore as much a governance challenge as a technical one.

Emerging frameworks, such as the UNTP, aim to enable decentralised cross-system data exchange. In a context of intensifying geopolitical competition, decentralised data governance is increasingly important. However, awareness and operational understanding remain uneven, particularly among midstream and downstream firms and government stakeholders. Broader uptake will depend on sector-specific adaptation, inclusive design, capacity building and practical demonstration of operational relevance.

8.2. Aligning traceability with producer country agendas

Traceability initiatives often reflect downstream regulatory and risk management priorities more than upstream realities. Links to producer-country objectives such as revenue mobilisation, market access and domestic value addition remain underdeveloped. As a result, many producer-country stakeholders experience traceability primarily as an administrative burden rather than a strategic opportunity.

Correcting this imbalance requires early and meaningful engagement

between standard setters, industry actors, regulators, producer-country governments and corporate actors. Traceability depends on active public-sector participation in mining jurisdictions, where governments regulate extraction and trade, issue certifications and provide the institutional foundation for company compliance.

Shared interests should be identified early and solutions co-designed, not introduced once core parameters are fixed. This research indicates that every producer country will have both something to contribute and something to gain from stronger traceability systems. One practical pathway is to promote interoperability with emerging national mineral governance platforms and administrative processes in producer countries. Examples include SIMBARA in Indonesia, SEM 2.0 in Chile and MOSES in Zambia. While these systems may not yet meet all downstream regulatory expectations, they establish foundational data infrastructure that can anchor future traceability integration.

8.3. Leaving no one behind: inclusion of ASM

Traceability programmes have generated important lessons on ways to engage the ASM sector. However, scalable solutions remain difficult, due to the subsector's persistent informality, limited electricity and connectivity in ming areas, hardware constraints and gaps in digital literacy.

A rigid insistence on comprehensive end-to-end traceability risks excluding ASM entirely. Such exclusion would be socially unsustainable and economically counterproductive. ASM provides livelihoods for millions and contributes substantially to the global production of several critical minerals, with the potential to fill prospective supply gaps. Yet commercial incentives for long-term inclusion are often weak.

In practice, feasibility depends less on sophisticated digital features than on pragmatic operating conditions and managed uncertainty that prioritises progressive improvement over binary pass or fail models. Rather than focusing on complete granular tracking of every transaction from the origin mine site, engagement can begin with key intermediaries such as cooperatives or traders/aggregators, to enable gradual expansion of traceability coverage upstream.

Linking traceability to more inclusive and functional operating structures is equally important. Improved access to finance, fairer pricing mechanisms, tax incentives and investment in measurement and processing equipment can support participation and progressive integration of ASM into formal markets.

8.4. Financing traceability: balancing costs and benefits

Sustainable financing remains a structural dilemma: who pays for traceability? Regulators and downstream firms increasingly require traceability, yet no single actor is positioned to finance shared infrastructure across the full value chain. Existing models, including licensed software, privately funded corporate systems and publicly financed programmes, have not proven scalable across the full diversity of actors in mineral value chains. The result is a patchwork of systems and an uneven distribution of costs and benefits across the supply chains. Downstream actors often capture compliance and reputational gains, while upstream actors bear disproportionate implementation burdens.

Beyond prioritisation and verification, long-term scalability requires reframing traceability not as a discretionary compliance add-on, but as shared operational infrastructure underpinning inventory management, supply chain visibility and resilience.

Hybrid financing models which combines private investment, regulatory mandates and targeted public or donor support will likely prove necessary. Cost-sharing arrangements should better reflect the distribution of benefits, and investment in interoperable infrastructure should be prioritised to reduce duplication and long-term costs.

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Annex 1: Lessons learned from traceability in the agri-food sector

Experiences from the agri-food sector provide valuable insights into how traceability systems evolve in response to operational risks and regulatory pressure. Similar to critical minerals, agri-food supply chains have long faced needs for transparency and accountability, as well as challenges such as limited interoperability and gaps in verification. While the two sectors differ structurally in their production and governance models, the agri-food experience illustrates how targeted regulatory and governance measures, including standardisation, baseline minimum requirements and consideration of implementation costs, can support traceability in moving from fragmented initiatives towards system-wide adoption.

Foundations of traceability development in the agri-food sector

Early traceability approaches emerged in response to a series of high-profile health and safety incidents. Mercury contamination in fish in 1970 and radioactivity detected in lamb in 1986[3] catalysed regulatory efforts to track origin and movement more systematically in order to manage risks to consumers. Institutional interventions followed. After the second major outbreak of mad cow disease in Europe in 1996, the EU established an agricultural traceability framework to strengthen food safety oversight and restore consumer confidence[4]. These episodes show how regulatory action helped embed traceability into routine industry practice.

Isotopic verification approaches in the food sector

In the food sector, structured traceability has been built through CoC standards and certification requirements, which support rapid source identification during contamination events and enable targeted recalls. For example, the Aquaculture Stewardship Council (ASC) maintains a CoC Module to support traceability and segregation of ASC-certified seafood products across the supply chain[5]. Similarly, GLOBALG.A.P. - which sets standards for crops, livestock, farmed seafood and animal feed - provides a CoC Standard that helps supply chain actors keep certified and non-certified products separate, identifiable and traceable[6].

However, even with integrity mechanisms such as audits, certification schemes have inherent limits, making over-reliance risky. Certification is often narrow in scope, costly and based on periodic audits, providing only partial and largely static visibility of material flows[7]. In response, parts of the food sector have adopted complementary approaches, including analytical techniques and more dynamic, system-based models that enable continuous data capture and monitoring[8]. This helps explain the

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growing emphasis on digitised traceability systems alongside certification-based assurance. External shocks - most notably the COVID-19 pandemic - further accelerated adoption of digital traceability across the food sector, particularly in food production and consumption[9].

For this purpose, food-sector traceability relies increasingly on scientific authentication methods such as stable isotope ratio analysis (SIRA), to substantiate origin claims where documentation alone may be insufficient. Because SIRA is relatively costly, it is applied selectively, including in commodity-specific schemes such as wine and protected-origin products where value, risk or regulatory requirements justify the investment.

Stable isotope compositions act as a chemical footprint shaped by local environmental conditions and, in some cases, production and feeding practices[10]. Each geographic region creates a specific isotopic pattern due to unique environmental factors. Comparing a product's isotopic profile with known regional patterns can help verify production origin and detect misrepresentation or fraud[11]. For example, the UK Food Standards Agency (FSA) recognises SIRA as a method to verify if the origin testing outputs are consistent with labelling claims[12]. Under the EU's Protected Designation of Origin (PDO) scheme, certified products must provide verifiable evidence that their specific qualities derive from the geographical environment in which they are produced[13]. SIRA has been used to authenticate provenance claims to detect commercial fraud[14], given PDO certified products often command higher prices, making them vulnerable to adulteration and mislabelling[15].

However, robust application depends on well-substantiated reference datasets from authentic samples, which are costly to build and maintain, prompting complementary use of modelling approaches to predict expected isotopic signatures[16].

Isotopic verification potential in the minerals sector

In the chemical domain, various mineral traceability methods have been tested. Mineral deposits, like agricultural products, retain distinct geological and geochemical signatures that can link processed minerals and metals back to their source, forming a natural basis for traceability[17]. Analytical proof of origin (APO), also known as fingerprinting, uses these signatures to determine provenance based on intrinsic material properties.

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However, scalability remains a key limitation. APO typically depends on reference datasets that capture the range of signatures across potential source deposits, so that tested materials can be compared against a validated baseline. Building and maintaining such databases is resource-intensive, and applicability can be constrained by processing and blending that dilute or obscure diagnostic signatures.

To date, analytical fingerprinting has been most developed for tin, tantalum and tungsten[18], reflecting heightened scrutiny of these “conflict minerals” in multiple jurisdictions. For lithium, a study by Desaulty et al. (2022)[19] has shown that fingerprinting is a useful tool for origin determination. A preliminary study by Dietrich (2024)[20] provides an APO methodology for graphite provenance verification. Nordic Innovation’s geo-fingerprinting proof-of-concept for rare earth elements similarly suggests that a limited set of trace elements and isotopes can survive refining and remain informative for origin verification[21]. Currently, the EU-funded Horizon Europe project MaDiTraCe is developing and testing digital, geochemical and artificial fingerprinting solutions for CRM, including lithium, cobalt, graphite and rare earth elements[22].

Although APO methods are not yet routinely integrated into prevailing sustainability standards, they have commercial potential as complementary verification mechanisms within broader traceability systems[23]. However, as with SIRA, cost remains a barrier, as does the need for extensive reference data and interoperable analytical and data-sharing standards. Therefore, effective APO testing depends on coordinated reference sampling, shared standards and supply chain cooperation. Progress in these areas remains limited to date. When weighing up the potential of APO methods, an important proportionality question must be considered: how critical is origin verification in a given context, and does the added level of assurance justify the associated financial and coordination costs? The scientific basis for APO is well established, but its scalability depends less on analytical capability than on viable cost-sharing arrangements, sustained funding models and clear governance guardrails. These constraints make fingerprinting most feasible for higher-risk or higher-value materials[24], where the need for enhanced assurance may be justified.

Transferable lessons from the food sector

To address fragmented data systems, limited interoperability, a lack of common standards and cost implications for supply chain actors, the food sector has introduced several targeted measures:

- **Establishing common data standards through stakeholder engagement**: Established in 2020, the Global Dialogue on Seafood Traceability (GDST) Standard

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sets out the minimum key data elements that should be recorded and shared in GDST-compliant seafood supply chains, and defines the technical formats and nomenclature needed for interoperable data exchange[25]. Standardised formats allow systems to exchange information with less manual intervention, lowering implementation costs and creating a shared technical language for consistent traceability practice.

- **Encouraging cost-reduction and affordable adoption:** To prevent digital traceability from becoming a cost barrier, the U.S. Food and Drug Administration's (FDA) *New Era of Smarter Food Safety* initiative has explored "low-cost or no-cost" tech-enabled traceability options accessible to operators of all sizes[26]. Building on this initiative, the Institute of Food Technologists (IFT) evaluated digital systems against detailed cost criteria, including data collection, training, hardware and maintenance, to identify scalable, cost-effective solutions[27]. These efforts aim to reduce burdens on smaller producers and help ensure that system-wide traceability advancements do not disproportionately exclude actors with limited resources.
- **Introducing mandatory baseline traceability requirements:** Many major food-importing jurisdictions have strengthened legal obligations for traceability, commonly requiring operators to record who they received a product from and who they supplied it to ("one step back, one step forward")[28]. In the EU, the General Food Law requires traceability across stages of production, processing and distribution[29]. Japan's beef and rice rules go further by mandating product-specific identification numbers carried from farm to final packaging[30]. These measures establish baseline expectations for data capture and help reduce fragmentation across supply chains.

Together, these examples suggest that traceability uptake increases when minimum requirements are clearly defined, data capture is standardised, costs and administrative burdens are addressed, and stakeholder needs inform system design. Drawing on the food sector experience, this section highlights the following conclusions relevant to mineral supply chains:

- **Certification provides a baseline.** Certification schemes can help organise and document material flows, but their effectiveness is constrained by scope, cost, supply chain complexity and reliance on periodic audits. More reliable traceability typically combines certification with routine data capture and targeted verification.

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- **Clear governance frameworks drive uptake.** Traceability scales when embedded in regulatory and risk-management structures instead of being treated as stand-alone solutions. As noted in Section 2.1, regulatory fragmentation can constrain uptake. Convergence around baseline data elements and common traceability nomenclature (as seen in parts of the agri-food sector) can encourage the type of governance evolution that enables more consistent uptake. Clear governance signals also strengthen the business case and wider value proposition for traceability beyond mandatory compliance.

- **Standardisation and interoperability enable scale.** The minerals sector has strong stakeholder platforms (e.g., ICMM, RMI, LBMA), but progress is constrained by the absence of harmonised approaches. Shared data standards and interoperable systems reduce duplication, lower costs and enhance uptake. Initiatives such as the UNTP (see Box 3) and emerging sector-specific derivatives such as the Responsible Business Alliance's (RBA) Responsible Business Transparency Protocol (RBTP), seek to address this gap by establishing common data models and interoperability standards. Operationally, traceability architectures are likely to evolve through sector-specific adaptations of shared standards, shaped by multi-stakeholder initiatives and industry. Greater cross-recognition between initiatives (e.g., through alignment of core data elements) can reduce reporting burdens and strengthen incentives for participation, thereby providing clearer pathways for multiple systems to be aligned while achieving scale.

- **Cost and inclusion shape effectiveness**. Traceability uptake is closely linked to cost. While the fair distribution of traceability-related costs across supply chains remains a largely unresolved challenge, wider adoption is more likely where compliance costs are low and responsibilities for actions are more defined and evenly shared. As illustrated in the food sector, interventions to lower costs can support the inclusion of smaller actors. In mineral supply chains, this may require strengthening the capacity and interoperability of state-owned mineral governance systems and embedding traceability functions within existing administrative and data infrastructures rather than creating parallel structures (see Section 7.4).

  Verification remains a distinct challenge. Digital and paper-based systems can improve transparency, but do not, on their own, verify key claims. Selective use of scientific tools can strengthen origin verification and support downstream differentiation where risk, value, or regulation justify the cost, but may also disadvantage producers unable to comply if requirements are not designed with inclusion in mind.

Annex 2: The role of ASM in producer countries

ASM is expected to play an increasingly important role in critical mineral supply chains. Although not all critical minerals are technically or economically suited for artisanal extraction, many are, as illustrated in Table 1. New and reliable sources of critical minerals will be required to meet current and projected demand, particularly for the energy transition[31]. ASM already contributes materially to global supply. For example, it accounts for approximately 25 percent of global tantalum and tin production[32].

ASM's prominence in many producer countries means it will remain an important component of upstream supply landscapes. In Chile, for instance, artisanal copper production generated export revenues of USD 117 million in 2018, equivalent to 0.3 percent of national copper exports. While modest at the national scale, this contribution is significant in local economic contexts. Evidence also shows that ASM production can respond more quickly to market dynamics than some large-scale operations, illustrating its potential to adjust more rapidly to fluctuations in commodity prices associated with low-carbon technology demand[33].

Table 1: Overview of ASM potential in CRM supply chains[34].

Potential to be sourced through ASM	Critical mineral
High	Chromium
	Cobalt
	Copper
	Lithium (pegmatite)
	Platinum
	Tin
	Tungsten
	Zinc
	Niobium
Moderate	Antimony
	Barite

Given ASM's current and potential contribution to critical mineral supply, sourcing companies will increasingly need to consider how they engage with this part of the sector and contribute to building a safer, more transparent and more resilient ASM supply[35]. Ensuring that ASM is not excluded from traceability efforts and due diligence systems will therefore be important, both for maintaining supply continuity and for supporting capacity-building that enables artisanal and small-scale miners to participate more effectively in regulated markets.

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[31] International Institute for Sustainable Development. (2024). *Artisanal and small-scale mining in critical minerals*. https://www.iisd.org/system/files/2024-12/artisanal-small-scale-mining-critical-minerals.pdf

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[34] Source: Adapted from: International Institute for Sustainable Development. (2024). *Artisanal and small-scale mining in critical minerals*. https://www.iisd.org/system/files/2024-12/artisanal-small-scale-mining-critical-minerals.pdf

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Challenges to integrating ASM into traceability and due diligence systems

This section summarises key challenges affecting the inclusion of ASM within traceability and due diligence systems.

Legalisation of ASM

In several producer countries, legal frameworks governing ASM are incomplete, inconsistently implemented, or absent. This weakens oversight and provenance control for minerals originating from ASM[36]. ASM is often seen as economically marginal and excluded from public support for the extractive sector[37]. Where regulation does not offer clear, accessible licensing and legalisation pathways, ASM activity persists informally, limiting its verifiable integration into traceability systems. Country experiences provide insight into workable legalisation mechanisms to increase ASM participation:

- **Indonesia** has no dedicated ASM framework. Community mining permits exist but are rarely issued, leaving ASM widespread yet largely unregulated[38]. ASM's contribution to nickel output is uncertain because activity is often informal and/or subsumed within large-scale operations. Estimates suggest ASM may account for around 25 percent of recent production[39]. In this context, systems such as SIMBARA lack reconciliation between mine outputs and smelter inputs, and ASM marginalisation contributes to observed discrepancies[40].
- **Tanzania** saw the number of Primary Mining Licences (PMLs) for ASM increase from 35 in 1999 to 5,171 by 2016, linked to more efficient processing and the designation of exclusive ASM areas. By 2017, 36 ASM-designated areas covering 2,438 km² held 8,800 PMLs, reflecting substantial uptake under decentralised licensing via Zonal Mines Offices. However, the government still lacks a central repository for ASM data, making information verification difficult[41].

Remote locations and weak infrastructure

Traceability implementation is shaped by the geographical and infrastructural conditions in which mining takes place. Many ASM and industrial sites are located in remote areas with limited state presence, weak transport links, unreliable electricity, high illiteracy rates and constrained digital connectivity. These conditions constrain the feasibility and reliability of traceability systems and increase the risks of data gaps and smuggling[42].

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[40] Payne Institute for Public Policy. (2025, April 24). *Analysis on ASM role in Indonesian nickel production*. https://payneinstitute.mines.edu/analysis-on-asm-role-in-indonesian-nickel-production/

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In DRC's cobalt sector, for instance, artisanal mining often occurs in rural, harder-to-monitor areas with limited state presence[43]. In this context, there are frequent reports of artisanal production being introduced into ostensibly legal supply chains at aggregation points, where material from multiple sources is combined, undermining provenance control[44].

The limitations of grouping artisanal mining (AM) and small-scale mining (SSM)

AM and SSM are generally treated as a single category in regulation and industry practice, despite being structurally distinct[45]. AM typically involves low investment, high labour intensity and variable organisation, whereas modern SSM is more mechanised, regulated and suited to smaller high-grade deposits. Treating them as interchangeable obscures these differences and can lead compliance systems to assume a single set of capabilities and risk profiles across all non-large-scale actors[46].

This misclassification can distort traceability design. Provenance is generally easier to establish for large-scale mines than for AM/SSM, yet requirements are often applied uniformly: SSM may be subjected to controls designed for informal AM, while AM faces obligations it cannot meet. Uniform requirements can (i) overburden AM, (ii) underestimate the regulated potential of SSM and (iii) restrict upstream participation.

Chile's state-owned mining enterprise ENAMI (Empresa Nacional de Minería) illustrates a more differentiated approach. It distinguishes between AM and SSM copper mining, provides legal market access through offtake purchasing and offers technical and operational support beyond licensing (such as geological data, processing and commercialisation services)[47]. ENAMI has channelled around USD 8 million annually through Decree 76, a public support scheme for ASM, to provide finance, processing units, and commercialisation services to small- and medium-scale operators. The World Bank promoted the ENAMI model in Tanzania as a pathway for ASM formalisation[48]. Evidence from Chile, however, suggests that while legalisation has been relatively successful, broader formalisation outcomes remain uneven and ENAMI faces constraints in modernising its systems[49].

From a traceability perspective, ENAMI nonetheless illustrates the value of public purchasing and support models as practical entry points: where such institutions exist, traceability requirements can be integrated into established commercial and support arrangements rather than imposed as standalone obligations that ignore differences in capacity between AM and SSM operators.

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