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Beyond Traceability: Leveraging Opportunities and Innovation in Chain of Custody Standards for the Mining Industry

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Abstract

Organisations are increasingly adopting the Chain of Custody (CoC) standards in the mining industry to enhance the traceability of minerals. It ensures that the minerals they have received are from credible sources and accompanied by verifiable information. However, unlikeother industries such as timber, where the effectiveness and benefits of CoC standards are mainly explored, this study subtly shifts the focus towards identifying strategic opportunities and innovation areas within the CoC standards that could extend beyond traceability. Four CoC standards were selected, and their provisions examined. It was found that implementing these requirements could not only enhance transparency but also support broader sustainability goals across the entire value chain. The study also identifies several challenges that could act as barriers to the CoC system, and these are seen as opportunities for innovative approaches to enhance the effectiveness of the standards. These are labelled as transformative innovation areas, and while they do include blockchains and analytical proof of origin technologies, this study also seeks to advocate for solutions that are more pragmatic and scalable. By identifying opportunities and areas of innovation, the findings will help improve the practical implementation of the standards and suggest areas for future evaluations of effectiveness that could consider aspects beyond traceability, such as sustainability and transparency.

Keywords: chain of custody; traceability; supply chain; sustainability; mining operations

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1. Introduction

1.1. Background

The mining industry has long been grappling with a tarnished image, associated with social injustice, environmental degradation, and economic risks, which has instigated the stakeholders to take action. Protests, legal disputes, and roadblocks became a persistent theme, and the repercussions of these activities have also impacted the industry's operations, consequently affecting the regional economy. The reason is that they are under strict scrutiny from stakeholders, primarily due to their position in the supply chain and the consumer-facing nature of their products. These are also known as focal firms [1], and they must ensure that their supply chains are not complicit in negative activities, due to regulatory and stakeholder pressure, including that of consumers and investors.

Complicity does have consequences, as evident in the recent lawsuit against Apple subsidiaries in France and Belgium for sourcing conflict minerals [2]. The list continues to include other tech giants and renowned automotive companies, all of which have been brought into the limelight due to activities at their suppliers [3,4]. With a majority of the risks prevalent in the deep upstream layers, it becomes a trying task for downstream companies to identify these risks, assess them, and either mitigate or prevent their occurrence. However, there is a limit to their visible horizon, and more often than not, organisations cannot see beyond a few tiers in their supply chain [5]. It is said that larger downstream organisations can have more than a thousand suppliers distributed across multiple tiers [6]. Even if attempts are made to map out the actors in the supply chain, a multitude of actors with blurred roles remain present in the upstream layers [6]. Furthermore, minerals are considered undifferentiated goods [7], adding yet another layer of complexity to verifying their origin.

The futile attempts made by larger organisations are evident in a study conducted by GAO [8]. The report states that, despite the Dodd–Frank Act's requirement to disclose minerals associated with conflict-affected and high-risk areas (CAHRA), only around half of the registered companies have assessed the possibility of whether their products contain conflict minerals. Of those, about 53% could not confirm the origin of their minerals. With mounting concerns and pressure on them, the downstream actors in the supply chain should implement measures to safeguard their reputation.

CoC is a method that enables downstream actors in the supply chain to gain a better understanding of the upstream actors, their activities, and the provenance of the minerals. Additionally, it provides an opportunity to actively mitigate risks in the supply chain and deliver relevant information to stakeholders. CoC is defined by ISO/DIS 22095 [9] as a means by which inputs, outputs, and their associated attributes are transferred, monitored, and controlled as they move down the supply chain. As represented in Figure 1, the flow of material designated by an arrow is also accompanied by information regarding the materials and suppliers at each stage of the supply chain.

Figure 1. Representation of CoC in the mineral raw materials supply chain, in which the arrow represents the flow of materials and flow of information in the CoC document.

While regulatory frameworks like the EU Conflict Minerals and the Battery Regulation require the implementation of a CoC system, there is a lack of guidance on how to implement it. In contrast, the voluntary CoC standards, such as the Aluminium Stewardship Initiative (ASI), the Initiative for Responsible Mining Assurance (IRMA), the Copper Mark, and the Responsible Jewellery Council (RJC), outline specific criteria that must be fulfilled for a CoC along with guidance documents. These voluntary standards serve as a form of private governance, providing a bridge to help organisations meet regulatory requirements [10]. Most existing studies on CoC have focused mainly on regulations and their role in responsible sourcing or corporate accountability [11–13]. Despite the growing attention to responsible sourcing, which involves managing environmental, social and governance (ESG) information within the supply chain [11], very limited attention has been given to CoC as a standalone topic. This study addresses the notable gap in the literature regarding CoC in the mining industry. It extends beyond the regulatory lens to evaluate

how provisions of the CoC standards can contribute to broader sustainability objectives, which include ESG impacts across the supply chain, as well as traceability. Moreover, it explores areas that could benefit from innovative transformation to facilitate the effective implementation of a CoC system.

1.2. Problem Statement

CoC as an approach can help the downstream organisations to ascertain the origin of materials and or ensure materials are procured responsibly, to avoid complicity with ESG risks in the supply chain, and voluntary CoC standards aid the organisations in the practical implementation of this system. However, little research has explored the areas where these CoC standards might contribute to broader issues, such as sustainability, beyond traceability. The lack of clarity regarding its potential hinders the actors in the supply chain from effectively meeting stakeholder demands and upholding responsible practices. Therefore, it is necessary to reevaluate the CoC standard provisions and see how they can be leveraged to enhance the effectiveness and strategic value of CoC systems.

1.3. Aim & Scope

This study advances the understanding of CoC standards in the mining industry by examining the provisions of four selected CoC standards. It identifies areas that could address other objectives or concerns faced by the downstream actors in addition to traceability. Furthermore, it considers the types of challenges that may arise and prevent the effectiveness of a CoC system, and assesses the potential of innovative approaches to resolve these barriers. Therefore, the study aims to explore selected CoC standards and answer the following research question:

What strategic opportunities can be derived from the implementation of the current CoC certification schemes, and how can downstream actors take advantage of these opportunities and manage the challenges through innovative approaches?

2. Theoretical Aspects of Reference

2.1. CoC System and Models

As already defined, the CoC system involves tracking minerals from the extraction of raw materials to the final product. It can employ five CoC models, either single or in conjunction, which are described as follows:

Separation models include identity-preserved and segregation. In the event of identity preserved, the primary objective is to maintain the origin, and strict controls are established to keep materials separate throughout the supply chain, even if they are certified. Segregation is comparatively less strict, as it allows the mixing of certified materials regardless of their source, but keeps them separate from materials provided by non-certified suppliers [9,14]. In practice, the separation models can be costly, and such stringent controls may be more effective for managing high-risk and high-value materials. This approach is also observed in the case of standards, where RJC restricts organisations to the use of separation models as it deals with gold and platinum group metals.

Mixing models: These models consist of controlled blending and mass balance models, the latter of which is further categorised into the rolling percentage average method and the credit method. They permit the mixing of certified and non-certified materials. In controlled blending, mixing is allowed between certified and non-certified materials, but the percentage of the former is always known and is accurately stated. For the mass balance models, both allow organisations the flexibility to source certified materials over a period of time, as long as the certified outputs do not exceed the inputs within the defined accounting period (normally not exceeding 12 months) and the associated claims

are upheld. Compared to the separation models, it is less costly and is practically and economically feasible to implement, as it does not require stringent controls. However, on the other hand, the origin of the materials is lost, as is the traceability aspect. It could be implemented in handling materials which is not under the scrutiny of regulations or associated with human rights concerns. An overview of the strengths and weaknesses, along with the implications for the mining industry, is provided in Table 1.

Table 1. Overview of the strengths & weaknesses of CoC models and implications for the mining industry.

	Identity Preserved	**Segregation**	**Controlled Blending**	**Mass Balance**	**Book & Claim**
Strengths	Assurance of origin	Assurance of certified materials in the product	Assures a certain percentage of certified material is present in the product	Flexible, scalable and requires fewer stringent controls	Flexibility, scalability and can be adopted by actors with no access to certified materials.
Weaknesses	Costly and stringent controls	Comparatively less costly and less stringent controls compared to identity-preserved	Partial loss of traceability and a complex procedure to determine the percentage of material	Loss of traceability	No link between materials and administrative controls, so loss of traceability
Implications for the mining industry	More suitable for high-risk and high-value materials like 3TG	To ensure regulatory compliance, for instance, for battery materials to meet the requirements of the EU Battery Regulation	For bulk minerals, where a certain percentage of assurance regarding responsible sourcing is required	For bulk and low-risk minerals where segregation is not feasible	Suitable for ASMs which can sell credits for their certified materials when there is no demand, and also for larger organisations to support responsible sourcing

There is a possibility that more than one CoC model is implemented, and when such products are mixed, the claim of the lower model is adopted. An example is that identity preserved with segregation can only claim segregation on the products [9,14].

The final model is a book and claim system, where the movement of physical materials and administrative records is decoupled. There is no physical tracking of the materials, as the claim associated with the certified material is sold as credits on a platform from which other organisations can buy and make claims. The physical material itself is sold as non-certified. The claims allowed demonstrate their support for responsible sourcing by purchasing or redeeming the credits. Such models could be beneficial for organisations that do not have the possibility of procuring certified materials in their immediate vicinity, but would like to contribute to promoting responsible practices in their supply chain. Moreover, it is also argued that such a model could help organisations with limited resources to adopt CoC models as comparatively less strict internal controls are required for material separation and mixing [15,16]. One important risk that could arise from using a book and claim model is the potential for double-counting credits, and strict mechanisms should be in place to prevent its occurrence [17].

The certified materials are reconciled within the accounting period, also known as inventory balancing, to ensure that the outputs claimed do not exceed the available certified inputs. A surplus or positive balance is permitted in the mass balance, allowing the additional credit to be carried over to the next accounting period. Under special circumstances, such as force majeure, organisations are permitted to reach a negative balance, which must be accounted for within the following accounting period [18].

2.2. Status of Implementation of Chain of Custody Standards in the Mining Industry

Standards are voluntary initiatives that provide performance criteria through technical, physical, or procedural characteristics [19]. Based on the degree of fulfilment, organisations can communicate relevant information in the form of certificates or product-related labels [20]. Similarly, the CoC standards outline the requirements for sourcing materials from suppliers responsibly, handling them in accordance with the CoC models, and providing information regarding the materials to the next actor in the supply chain or to the end-consumer in the form of claims. For instance, claims related to identity preserved are the origin of the product; in the case of segregation, it is the presence of 100% certified materials. Controlled blending enables the claim of a specific percentage of certified materials, provided all the requirements of the standards are met. For mass balance, the claim pertains to the responsible sourcing of a certain percentage of materials, as certified materials may or may not be present in the product.

While information is imparted on the origin and authenticity of the goods and services, customers remain doubtful of the claims made [21]. Reports such as The ITSCI (International Tin Supply Chain Initiative) Laundromat [22] exacerbate the situation, demonstrating that the scepticism of stakeholders was warranted and the claims unsubstantiated. This programme strives to maintain a CoC of the minerals from conflict regions by implementing a bag and tag system and aligning with the OECD due diligence guidance. Yet, the investigative report by Global Witness [22] shows that this scheme failed to eliminate the entry of conflict minerals into the supply chain, which in turn allowed them to be incorporated into products of renowned brands such as Apple, Intel, and Tesla.

Impacts of CoC standards in other industries, like wood, concerning the effectiveness and benefits of the Forest Stewardship Council (FSC) CoC certification [23,24] and Programme for the Endorsement of Forest Certification (PEFC) [25], and the Marine Stewardship Council (MSC) CoC standard for fish [26,27], have been assessed. Guan et al. [23], for instance, noted that CoC schemes, in the case of FSC, are being rapidly adopted to access markets, and the benefits of these schemes are not equally distributed across all products. For the MSC CoC certification assessment, Iue et al. [27] determined that downstream actors were more likely to be certified, as they were consumer-facing. The costs of getting certified acted as a barrier; in response, incentives must be offered to persuade organisations to get recertified. In sharp contrast, the adoption barriersand benefits of the standards in the mining industry have not been explored.

Building on these gaps in the role of CoC in the mining industry, four CoC standards, ASI, IRMA, Copper Mark, and RJC, were selected for this study based on their appearance in the comparative overview reports of sustainability standards in the mining industry. Erdmann and Franken [28], Sturman et al. [29], and Potts et al. [30] include the most relevant CoC standards and also provide examples of their uptake. These standards offer auditable provisions which can act as a basis for a comparative assessment and can help to identify areas where CoC can contribute to broader sustainability objectives and require transformative innovations.

3. Key Findings

Table 2 provides an overview of the standards. CoC standards supplement the sustainability and performance standards in the mining industry, demonstrating responsible mining practices. For instance, the RJC CoC standard complements the RJC's Code of Practices, and similarly, the ASI CoC Standard complements the ASI Performance Standards. It is observed that the CoC standards differ in two aspects overall: firstly, in the scope of minerals covered by each standard, and secondly, in the type of CoC models that the standard can implement. IRMA and Copper Mark allow the implementation of multiple models. In contrast, ASI and RJC strictly allow a single model, with mass balance for the former, and the latter only separation models.

Table 2. Overview of the selected standards.

	IRMA	**ASI**	**RJC**	**Copper Mark**
Version	1	2.1	2024 Version (2nd)	1
Year	2024	2023	2024	2022
Commodities coverage	All minerals	Bauxite, Alumina, Aluminium	Gold, PGMs (platinum, palladium and rhodium), Silver	Copper
Add on to	IRMA Standard for Responsible Mining	ASI Performance Standard	RJC Code of Practices	Copper Mark Responsible Production Criteria
Nature of certification	Voluntary	Voluntary	Voluntary	Voluntary
CoC model used	All models	Mass balance (credit method)	Segregation	Segregation and mass balance (credit method)
Governance	Multi-stakeholder governance	Not-for-profit multi-stakeholder governance	Multi-stakeholder governance	Multi-stakeholder governance

Regarding the extent of adoption of these standards, it has been reported that as of 2023, 82 entities were ASI CoC certified, representing an increase from 68 in 2022 [31]. RJC has an estimated 360 CoC-certified members since its launch [32]. However, for Copper Mark, only three were certified as of 2023 [33], as it is relatively new, similarly to IRMA. For the latter, the number of certified entities is not yet disclosed.

Table 3 presents the overall management system required to ensure the implementation of a CoC system, along with all the standards. They typically include this system within the organisation, such as roles and responsibilities, records management, and employee training etc. Among the reviewed standards, only IRMA mandates the need for an internal accounting system in place, like AMIRA P754 or similar, in addition to reconciliation and controls based on the type of CoC model used. In comparison, others have only included general components, such as reconciliation and controls based on the CoC model, as part of their internal material controls, but have not emphasised the requirement of an established internal accounting framework to be in place.

Table 3. Overview of the management criteria in CoC standards.

Management Criteria	Further Information
Roles and responsibilities	• Defined roles and responsibilities for the activities needed to maintain a CoC system • The presence of a responsible person to ensure conformity with the standard requirements
Records management	• Criteria to address data collection, validation, access, safety, storage and communication
Metal Accounting system	• The CoC system controls based on the model • Accounting period • Reconciliation of inventory • Conversion factor inclusion to account for material losses • Claims management depends on the CoC system • Mass balance: positive balance and negative balance
Communications and training	• Training of the employees who are handling the CoC material • Retention of all relevant internal and external communication related to the CoC system
Complaints procedure	• Documentation and sometimes reporting, as needed, of complaints received • Methodology of handling the complaints
Internal review	• Periodic reviews of the efficiency and effectiveness of the internal processes • Internal audit report findings • Updates or corrective actions are made to the system based on the review
Corrective actions for non-conformity	• Related to materials and supplier information • Corrective action in case of incorrect information and inconsistency with materials
Outsourcing	• Certified organisation maintaining custody of the materials despite outsourcing • Verification of the inputs from the outsourcing contractor • Corrective action in case of non-conformity

The management criteria include documentation, training for employees involved in handling the CoC material, and periodic internal evaluation, which is generally part of the governance frameworks in organisations and closely linked with the ISO 9001 [34] management system [35].

Although these systems are primarily designed for internal processes, they effectively form the basis of supply chain integration by providing provisions such as external communications, outsourcing to contractors, and corrective actions related to information or materials received from suppliers. Furthermore, findings from a Delphi study show that integrating ISO 9001 and supply chain management helped improve the triple bottom line of the organisation [36]. Standards encompassing carbon footprint can align with the regulation's prerequisites, offer the downstream players a clear view of stages with higher emissions, and facilitate targeted actions.

Table 4 represents the sourcing criteria established by the standards. All standards address primary and secondary materials, as well as material and supplier information verification provided along with the inputs. Any non-conformities detected in either should have corrective actions in place, as outlined in the previous table and applicable to primary

materials. However, due diligence requirements, such as Know Your Customer (KYC) procedures, are only included in some of the standards for suppliers of materials from secondary sources, traders, and non-CoC materials. Additionally, provisions regarding non-CoC materials are only addressed by ASI.

Table 4. Overview of the sourcing criteria of the CoC standards.

Sourcing Criteria	Further Information
CoC document	• Verification of information on the CoC document regarding CoC materials and the suppliers. • The following information is generally included in the CoC document: ○ General details: Date of issue, document number/reference number, a statement on the CoC documents stating that it conforms to the standard requirements, and the CoC model implemented ○ Issuer/seller information: Company name, address, certification number, certification start and end dates, responsible person ○ Receiver/buyer information: Company name, address, certification number ○ Material information: Qualitative and quantitative information, claims associated with the material or product, and a unique number of batch/lot ○ Additional information (optional): Supplementary information like technical details, sustainability information, specific certification claims
Secondary materials	• Due diligence measures like KYC and risk assessment • Determination of origin and checks to ensure the secondary nature of the input material, i.e., that it is not virgin material
Non-CoC materials	• Due diligence, risk assessment and mitigation

Responsible sourcing is an integral part of CoC, as it ensures that the CoC material is procured from a certified organisation which have met all the ESG and tracking requirements set by the standard. But the inclusion of non-CoC material in the scope of certification, which is only performed by ASI, will further enable the organisation to extend its responsible practices to all materials procured. It is specifically pertinent to operations that blend certified and non-certified materials under mixing models that there is a risk of introducing minerals associated with the CAHRAs, for instance, into the supply chain without proper due diligence protocols, thereby compromising material integrity. Such strategies are likely to be more widely adopted, considering that separation systems are costlier and require more stringent controls [37]. This approach will help cast a wider net to identify risks associated with social and environmental issues and unfair business practices at the suppliers, even if they are not certified.

Table 5 represents the handling and sales criteria. The claims are related only to the certified material and are dependent on the type of CoC model used. Claims related to separation models can facilitate alignment with international standards like the OECD Due Diligence Guidance and national regulations like the EU Conflict Minerals Regulation. However, in mass balance systems, there is an inherent tradeoff between technical scalability and traceability for the claims. The claims are then shifted to practices like ‘providing a

percentage of responsibly sourced minerals,' rather than the presence of certified material in the product claims. In either case, the claims form a medium of communication with the stakeholders.

Table 5. Overview of the handling and sales criteria.

Handling and Sales Criteria	Further Information
CoC model	• Material handling protocols depend on the CoC models • Determination of the critical control points where mixing of certified and non-certified materials could occur
CoC document	• Inclusion of information on CoC material • Inclusion of information on the supplier (refer to Table 5 for more details)
Claims	• Product-level claims following the models • Site-level claims following their practices and CoC models employed

4. Discussion

4.1. Strategic Opportunities

The standards include provisions for responsible sourcing, handling and claims. However, with standards gradually integrating voluntary ESG data, such as carbon emissions in the CoC document and due diligence information for materials from the CAHRA, it is evident that the CoC standards' existing requirements can be extended to include aspects beyond traceability and meet sustainability objectives as well.

The opportunities identified from the standard requirements:

(1) Inclusion of ESG aspects in sourcing and handling materials: using the same mode of information transfer, i.e., the CoC document for materials and suppliers, can also mandate the inclusion of information such as carbon footprint or due diligence practices when procuring minerals from the CAHRAs. Extend the scope of conducting due diligence of suppliers of non-CoC materials.

(2) Information for stakeholders and increased transparency as part of communications: possibility of disclosing the verified information to interested parties and integrating this information in disclosures to build trust in their practices and claims.

(3) Inclusiveness and consolidating supply chain actors in the scope: possibility of including ASMs in certification schemes by expanding the scope and recognising their efforts towards responsible practices. Detailed provisions for proactively seeking to integrate upstream actors by providing incentives or knowledge sharing to build their capabilities.

4.1.1. Inclusion of ESG Aspects in Sourcing and Handling Materials

The concept of CoC is a part of responsible sourcing [11], and gaining access to sustainability information along with the traceability information at each stage of the supply chain can provide a way to address the ESG risks actively by engaging directly with the suppliers and relevant stakeholders [38]. As observed, the CoC standards serve as an add-on to the performance standards in the mining industry, as shown in Table 2. With the implementation of the latter, verifiable information regarding ESG practices can be generated. Primarily, only supplier and material information is mandated to be provided to the next actor in the supply chain using the CoC document. Moreover, it is not mandatory, but most CoC standards include a provision to provide sustainability information, like carbon footprint, if necessary, along with objective evidence.

For instance, ASI allows the CoC document to include average carbon footprint information as well as the recycled content of the CoC material, which can contribute to the environmental pillar of sustainability. Similarly, RJC has outlined a framework for due diligence that is consistent with the OECD Due Diligence Guidance, which requires the disclosure of the origin of minerals if they are associated with the CAHRAs. This also helps to meet the regulatory requirements, such as the previously mentioned Dodd–Frank Act and the EU Conflict Minerals Regulation [39]. Furthermore, as shown in Table 4, there is an opportunity to improve the due diligence practices of suppliers of non-CoC materials as well. And this would mainly be needed for the standards which allow the use of controlled blending and mass balance models, to maintain the integrity of the entire product and not only for the CoC material in the product.

By making ESG information transfer mandatory, each player at every stage contributes to a greater collective effort, rather than relying solely on downstream players to identify risks in the supply chain. Furthermore, regulations, such as the EU's New Battery Regulation, will require manufacturers to report their total carbon footprint by demonstrating a link to the entire battery life cycle [40]. Standards encompassing carbon footprint can align with the regulation's prerequisites, offer the downstream players a clear view of stages with higher emissions, and facilitate targeted actions.

4.1.2. Information for Stakeholders and Increased Transparency as Part of Communications

On the one hand, downstream organisations require information regarding the actors in their supply chain and identify the associated ESG risks. On the other hand, suppliers are reluctant to disclose information about their suppliers and sub-suppliers. There is a general perception that their customers would reach out to their suppliers directly, and this might compromise their competitiveness in the market [41,42]. However, with a CoC in place, the information required by downstream actors can be shared with them in a controlled and standardised manner, which helps to alleviate concerns about confidentiality. This can include information about the processing steps, carbon footprint details, and all credible and relevant information, without requiring a full disclosure of the actors in the upstream and retaining their competitiveness in the market.

However, simply sharing information between organisations is not enough. Stakeholders, including consumers, investors, and NGOs, are now interested in the sustainability impacts and objectives of the supply chain activities [43,44]. The responsibility of communicating this information to the broader public disproportionately falls on the focal companies [45,46]. Customers want to know about the origin of the materials and the processes behind the manufacture of their products so they can make an informed decision regarding their purchase [47].

In addition to customers, NGOs and advocacy organisations work towards gaining this information and raising awareness regarding sustainability and due diligence issues related to procurement practices [38]. Government bodies expect organisations to adhere to the supply chain regulations and perform due diligence, specifically for those involved in the trade of the 3TG minerals [48]. A common form in which information about a company's activities and performance is disseminated to its stakeholders is through disclosures, such as sustainability reports [49,50] or product labels for the end-consumers.

Typically, after an audit procedure, an independent body issues a certificate representing conformity if all the CoC standard requirements are met. It is worth noting that not all audit procedures include a certification function. With the implementation of certification requirements and completion of the audit procedure, organisations can provide reliable and verified information to their stakeholders regarding the presence of certified material

and its origin, or demonstrate their support for responsible sourcing and practices; in other words, they can be more transparent [51].

4.1.3. Inclusiveness and Consolidating Supply Chain Actors in the Scope

As already stated, CoC will require that every actor in the supply chain, from the extraction of raw materials to the actors involved in the creation of the final product, be certified. It is also the case that larger organisations are under pressure from various stakeholders to implement such schemes due to their visible position in the supply chain. In this case, these organisations can push the supplier upstream to those with whom they have a direct contractual relationship to adopt the CoC certification. The challenge arises when trying to reach suppliers beyond tier 1, and a multitude of factors can contribute to preventing engagement and integration with all actors in their supply chain.

Supply chains are often fragmented, and production processes can span international boundaries, involving various regulatory requirements. It is illogical to presume the universality and uniformity of the law enforced, especially in less developed countries with low legal requirements and affinity towards procuring responsibly sourced minerals.

Moreover, sourcing of certified materials is challenging due to the resource-intensive nature of the certification requirements. Changes, for instance, in infrastructure, material handling methods, and employee training, are necessary to ensure they are aware of the standards' requirements. At the same time, they must internally evaluate their processes to confirm the effectiveness of the systems in place. Price premiums for supplying certified products could partially cover the cost of implementation and maintenance. Still, they can be a significant financial burden, especially for small and medium-sized companies, which could deter them from getting certified.

Vidal et al. [52] argue that the claims, which are part of the certification schemes, are a privilege for organisations that can afford them; in most cases, these are the larger ones. It tends to exclude the ASMs, which in recent decades are believed to have accounted for a significant share, i.e., 15–20% of the non-fuel mineral outputs [53]. It is an established notion that upstream actors possess fewer resources, which could prove more cumbersome for those present in the CAHRAs. In particular, these actors must invest more resources in conducting due diligence activities to identify risks associated with conflict, mitigate or prevent them and continuously monitor to prevent recurrence [54]. It can create an uneven playing field, limiting the capabilities of smaller or medium-sized organisations and affecting their competitiveness.

Therefore, certification schemes should strive to be inclusive, regardless of size. This is observed in the case of the RJC CoC certification standard, which also includes provisions for sourcing from artisanal and small-scale mining operations that have taken the initiative to formalise and integrate due diligence practices. Larger organisations could support the efforts of these small and medium-sized companies by providing financial support and incentives, as well as facilitating knowledge sharing through collaboration. While some standards do recognise the resource limitations of upstream actors in the supply chain, such as IRMA and RJC, this aspect could be more heavily emphasised in the standards' provisions. Provisions such as providing incentives, fostering collaboration, and sharing knowledge will help expand participation across the supply chain and enable even the small and medium-sized organisations to contribute to responsible sourcing. This also suggests that CoC standards should consider including stakeholder engagement mechanisms, which can help foster the faster adoption of standards across the supply chain.

4.2. Transformative Innovation Areas

The standards generally include the provisions for a CoC document or equivalent and retention of information that would determine the origin of the material. However, it has been discussed earlier how such systems can be severely limited, how CoC models, such as mass balance systems, could risk the infiltration of illegal or sanctioned minerals into the supply chain. To address this issue, the study also identifies areas where standards could introduce innovative solutions to ensure stronger verification mechanisms.

The transformative innovative areas that were identified are as follows:

(1) Chain of custody document: Provisions for technologies or systems to connect the nodes in the supply chain.
(2) Concrete determination of origin and tracking solutions: Solutions for determining origin are still in their infancy, limited in scope and scalability. Currently, the documentation system is the only feasible option; however, innovative solutions must be promoted, and standards can play a key role in their development and adoption.

4.2.1. Chain of Custody Document

The standards do not impose the use of technology, and the industry still primarily relies on paper systems. Time and again, it has been discussed how paper can be forged or modified, hindering the efficiency of traceability systems. An instance provided by Global Witness [22] of forged proof of payments demonstrated that it allowed CAHRA materials from unvalidated mines to infiltrate the formal supply chain. Criminal organisations often exploit these weaknesses in the system to make false claims and advance their illicit activities [55]. Such cases raise questions about the credibility of physically attached documents or those used to record information. Therefore, there is a dire need for real-time information from the CoC document, allowing for proactive monitoring of material movement and mitigation of risks [56].

One such emerging tool garnering notice due to its ability to enhance transparency and traceability is blockchain technology [57]. It can prevent information tampering, record changes in ownership and the origin of materials, and be time-stamped, secure, and safe. Despite the benefits it provides, its application in the mining sector remains contested. A majority of mining operations take place in remote locations, resulting in a shortage of skilled personnel and necessary infrastructure, as well as a lack of skills to manage such sophisticated technology. In addition, organisations must incur increased costs to implement blockchain technology, which is necessary to address energy costs and ensure interoperability with existing systems [38,50,57]. A major vulnerability of blockchains is the issue with reliable data input. Blockchains will merely preserve data integrity once it is entered, but if the data entered is inaccurate or falsified at the source, they will do nothing to detect the issue [58]. Despite the barriers to adoption, some industry pilots and initiatives have demonstrated a proof of concept, like the Ford Motor Company, for sourcing cobalt ethically [59], Circulor helping to track cobalt in the Democratic Republic of Congo, and Minespider integrating the Battery Passport with blockchain technology to not only ensure traceability of the materials but also to track ESG metrics for battery materials. However, the same article quotes the expert interview that highlights the issue of scalability, where larger companies are running pilots under controlled conditions [60]. Still, integration across the entire value chain, among diverse actors, is necessary to assess its transformative potential.

While blockchains can contribute to connecting the entire supply chain, they cannot act as a standalone system. Even the internal systems for tracking material flows within the organisation should be digitalised to enable effective material tracking. The IEA and OECD [61] specified four main components in their conceptual schema of mineral

traceability: supply chain collaboration, commodity-specific risk assessment, technical infrastructure, governance, and verification. According to the technical infrastructure component, the physical material must be linked to digital records to ensure tracking. This can be achieved through various tagging mechanisms, including radio-frequency identification tags (RFID), quick response codes (QR), or barcodes, which can be chosen based on the size and complexity of the organisation's operations. Alternatively, rather than integrating sophisticated technological tools that still have disadvantages and drawbacks to consider, a middle ground could be to mandate the connection of the node before and after in the supply chain, that could extend from a centralised system to include that of their trading partners, upstream and downstream, to enable the verification of information [62] and to digitise the internal tracking processes of each firm. CoC standards have also taken note of the use of technology in tracking, but have not tackled it comprehensively. For instance, the Copper Mark CoC standard recognises the importance of technology in traceability. However, it is still assessing how the technological aspects can be incorporated into the standard. In contrast, the FSC standard of the timber industry has recently introduced a digital platform, FSC Trace, which automates CoC information like volume summaries and helps to maintain oversight of the transactions across the supply chain [63].

Standards need to integrate provisions regarding technological aspects and support the creation of technological platforms in tandem with the standard development, which is crucial for establishing credibility in the information generated, and participants in the supply chain can actively manage the risks [56]. Some mandates, such as, standardised identifiers, data sharing rules, and event formats, as represented in Table 6, could be introduced to harmonise the approach to collecting data and effectively link the material to the digital records, making it easier to verify the provenance and reliability of the information [62].

Table 6. Example of how the physical and digital layers could connect the nodes in the supply chain (some elements were extracted from the GS1, 2017 standard).

Physical Layer		**Digital Layer**	
Product	Run-of-mine, concentrate, components, or final products, recycled materials, etc.	Standard identifiers	Assign lot or batch ID, organisation ID, shipment or transport ID
Process	Production, transformation, input or output quantities, conversion factor, etc.	Event records	Record shipping, who, what, where, when and why details
Transaction	Transportation documents, sales invoices, etc.	Verification	Maintain transaction IDs and conducting a three-way match method
CoC document	Origin, percentage of certified or recycled materials, etc.	Control of claims	Evaluate whether certified outputs are less than certified inputs in the defined accounting period and reconciliation of data

The CoC system mainly depends on internal controls such as training of the employees, identification of the critical points where certified and non-certified materials may be mixed, use of the correct conversion factors, etc., which form part of the governance frameworks to source, handle, and transfer the materials. Strict mechanisms are in place to source materials and to record and verify the information about the materials and suppliers, and in case the material is associated with CAHRA, additional due diligence checks are conducted.

A corrective action plan is in place to address any discrepancies that may be encountered at this stage.

Following this is the handling stage, where the certified materials are labelled and tracked through all stages of production, and protocols for the CoC models are adhered to in line with the standard requirements. Reconciliation of certified materials with the claims is necessary for organisations implementing a mass balance model. Generally, according to standard requirements, a report of the metal accounting procedures needs to be submitted to the certification body either annually or at the end of the accounting period. The final stage involves transferring the materials along with their associated claims, using a CoC document, if the next actor in the supply chain is certified. Compliance with the procedures is verified through the internal evaluations as well as third-party auditing. Although the system relies on strict internal material controls, the presence of technology will help to reinforce these controls and connect the different actors across the supply chain.

4.2.2. Concrete Determination of Origin and Tracking Solutions

Among the CoC models, identity preservation is the one that will enable the next actor in the supply chain to affirm that the material originated from a particular mine. But with a programme such as the iTSCi in place, minerals from unknown origins, like unvalidated mines and mines which are controlled by criminal organisations and fraught with human rights abuses, seeped into the formal supply chains [22]. One instance has already been discussed, namely the use of paper-based systems that could potentially transition to digital platforms. But there is still a risk of falsified information entering the system in the initial phases, which may go undetected.

Additionally, the identification of origin is currently an issue with the minerals from the CAHRAs and sanctioned countries. It is quite common to see reports and instances such as the following: gold exported from unknown origins from four South American countries accounting for more than 3080 tons [64]; difficulty in differentiating between recycled and virgin materials, and issuance of fake certificates of origin [65]; and refineries in India and China still processing gold from Russia, which is a sanctioned country [66].

Dietrich and Melcher [66] noted that analytical proof of origin, or analytical fingerprinting, is the only definitive way to prove the origin of minerals and address this vulnerable gap. It takes into consideration the innate properties of the raw materials, which are largely dependent on the geographic location from which they are extracted. It requires a combination of analytical processes. However, the scope of application of the method is still quite narrow and challenging, and only addresses some materials. For instance, it requires a database where all possible origins are stored, allowing the collected samples to be compared against them [67]. So far, analytical fingerprinting technology has been applied to tin, tungsten, and tantalum [68]. Currently, the EU Horizon project MaDiTraCe is in the process of integrating more minerals, such as lithium, cobalt, and graphite [69]. However, this method is still in the early stages of development. It is also quite expensive, which can limit scalability and may be more feasible for high-risk and high-value materials [67]. Similarly to blockchain, these solutions can be viewed as complementary tools to support CoC processes and enhance the credibility of the information.

Similar technology to identify the genus, family, or species of timber is also an integral part of forest certification, as the timber industry strives to keep illegal timber out of formal supply chains. Their efforts demonstrate that collaboration between stakeholders, such as FSC, with the World Resources Institute and the establishment of an open-source reference database can enhance the credibility of the CoC claims [70]. This is also added as part of their standard to allow the organisation to submit representative samples for testing and contribute to the FSC Supply Chain Integrity Program [71]. An identical approach is

also taken by the Marine Stewardship Council (MSC), which incorporates DNA testing of the fish to address fish mislabeling. This goes to prove that testing the material should be embedded into standard practices and conducted through independent audits.

Therefore, apart from strengthening the reliability of the information provided on documents and technological platforms, certification bodies could support these innovative chemical technological solutions by encouraging their adoption by adding them as part of the standard provisions, mainly for high-risk and high-value materials, rather than for all materials. They could do so by promoting them either during the certification process or by testing their feasibility in pilots.

4.2.3. Provisions and Practices for Improved CoC Implementation

Table 7 illustrates how the CoC standards could include provisions for overcoming the identified barriers to the faster and more effective implementation of a CoC system, and linking them to practices that organisations can carry out under the standard requirements. For example, including stakeholder engagement as a criterion in the standards and tiered requirements would help facilitate the uptake of certification for those with fewer resources, which is a strategic opportunity to expand inclusivity. This could be complemented with cost and knowledge sharing practices by the organisation. Finally, the last column shows how the two provisions and practices together can contribute to areas other than traceability and, at the same time, ensure that the integrity of the information generated.

Table 7. Barriers and responses within CoC standards.

Barriers to Faster Adoption and Effective Implementation of CoC	CoC Standard		Contribution
	Provisions	Practices	
Lack of resources of SMEs	Stakeholder engagement and inclusive requirements	Cost and knowledge sharing through training of suppliers, as well as providing incentives	Responsible sourcing regardless of the size of the organisation
Loss of information integrity	In addition to documentation, provisions to operate on digital platforms	Support pilots for innovative digital solutions like blockchains and chemical technologies Spot-checks using chemical technological solutions	Reduced risk of illegal materials entering the supply chain and information credibility
Controls limited to CoC materials	Include due diligence requirements for non-CoC materials	Collect 2nd- or 3rd-party verified ESG data from non-certified suppliers	Reliable data for sustainability reports and extended responsible sourcing practices, and not complicit in supply chain risks
Complex standard requirements for internal controls	Tiered requirements, with different levels like core and advanced. With advanced requirements mandated for materials which are high-risk and under the scrutiny of regulations, and core requirements for upstream actors	SMEs could start with core compliance requirements, which could then be gradually transitioned to more advanced requirements	Fulfil regulatory requirements while increasing the uptake of standards across the supply chain
Limited access to ESG and traceability information	Standardised information templates considering business confidentiality Specify disclosures required by different stakeholder groups	Publicly reporting ESG and traceability information of suppliers, and making it accessible to relevant stakeholders in alignment with standard reporting formats like Global Reporting Initiative Standards (GRI) and contributing to publicly accessible databases	Increased trust among stakeholders and transparency about practices

5. Conclusions

In conclusion, with regulations imposing traceability and CoC systems and stakeholders demanding responsible sourcing and operations in the supply chain, organisations

will have an affinity for doing business with certified suppliers, ensuring that the minerals they use do not originate from areas where human rights violations and detrimental environmental impacts are prevalent and to which they may become complicit. One way to achieve this, as discussed in the article, is through the implementation of a CoC system.

This study is among the first to examine CoC as a standalone topic in the mining sector, thereby addressing a critical gap in the literature. By assessing the four CoC standards, it identifies areas where CoC can contribute to broader sustainability objectives beyond traceability and where there is an opportunity to integrate innovative solutions, such as blockchains or material fingerprinting, to realise its full potential. From a practical perspective, with a CoC system in place, organisations can be compliant with regulations and, in addition, achieve transparency and improved risk management associated with ESG across organisational boundaries. This is an increasingly important aspect, especially with the growing scrutiny from investors and consumers, who place a greater emphasis on responsible practices. In addition, it also goes to show how this study advances the discussion on supply chain governance, as CoC contributes to stakeholder engagement and structures sustainability practices in the mining sector.

However, more importantly for future research, it is crucial to include upcoming standards like the CERA 4in1 and programmes like iTSCi in the analysis, and it should also capture the perspectives of industry actors on how they are navigating the complexities of implementation, how SMEs can overcome resource barriers and participate in these schemes, and how the use of certified materials aids in achieving measurable ESG performance. All the collected insights could help validate the identified strategic opportunities and, at the same time, allow existing standards to adopt a more inclusive and effective approach to achieve a CoC system.

Limitations of the Study

This study only considered four CoC standards; however, there are other standards addressing traceability and CoC elements to varying degrees, which are not included here. Only a few of the CoC certifications assessed were of global scope and led by northern certification schemes. It excludes the perspectives of the standards developed in the Global South or developing countries. Additionally, the study was primarily based on secondary sources and standard documents without empirical validation through case studies or interviews, and as a result, the findings are regarded as indicative. Future research could include empirical investigations to assess how CoC adoption contributes to measurable ESG outcomes and to what extent organisations of different sizes can overcome resource barriers and adopt CoC certification.

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Abbreviations

The following abbreviations are used in the manuscript:

CoC	Chain of Custody
ESG	Environmental, Social and Governance
QR	Quick Response
RFID	Radio Frequency Identification tags
CAHRA	Conflict-Affected and High-Risk Areas
iTSCi	International Tin Supply Chain Initiative
FSC	Forest Stewardship Initiative
NGO	Non-governmental Organisation
GRI	Global Reporting Initiative Standards
3TG	Tin, Tungsten, Tantalum and Gold

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