NO CARBON LEFT BEHIND: TOWARDS TRACEABLE BIOGENIC CARBON IN CONSTRUCTION VALUE CHAINS

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Abstract

Biobased construction materials store atmospheric carbon, yet current life cycle assessment and environmental product declaration practices represent biogenic carbon as aggregated indicators with limited traceability across value chains. This limits transparency, attribution, and credibility of carbon-related claims. This paper explores how blockchain-enabled system principles can address these deficiencies by treating biogenic carbon as a persistent, traceable state linked to material flows. Through an exploratory mapping onto bamboo value chains, we identify how such ledger-based logic can formalize carbon continuity, prevent double counting, and support auditable life cycle transitions. The paper contributes a conceptual framework for carbon ledger approaches in construction.

Introduction

Biobased construction materials such as bamboo and wood are increasingly promoted as key contributors to climate mitigation strategies in the built environment (Rincón et al., 2023). Their relevance stems from their ability to sequester atmospheric carbon during growth and to temporarily store this carbon in buildings and infrastructure (Bundi et al., 2024). As embodied carbon gains prominence alongside operational emissions, the question of how biogenic carbon is accounted for has become central to sustainability assessments in construction.

Current life cycle assessment (LCA) frameworks provide standardized methods to quantify environmental impacts, including biogenic carbon flows (Hellweg & i Canals, 2014). However, in practice, biogenic carbon is typically represented as an aggregated balance at product, building, or system level (Tellnes et al., 2017). Information about origin, transformation, ownership, temporal storage, and end-of-life fate is progressively abstracted away as materials move along value chains (Sayın et al., 2025). This abstraction limits transparency, complicates verification, and creates uncertainty when biogenic carbon is used to support climate claims or compensation mechanisms (Dwyer & Mowry, 2022).

These limitations are particularly pronounced in global and heterogeneous value chains, such as those associated with bamboo-based construction materials. Bamboo is harvested, processed, transformed, and assembled across multiple actors and locations, often with limited digital continuity between stages. While the material itself is inherently traceable in physical terms, the associated carbon information is not.

In parallel, digital technologies in construction have primarily focused on design coordination, simulation, and operational performance, while the underlying logic of carbon accounting has remained largely unchanged, reflecting broader institutional misalignments between technological innovation and adoption in the construction sector (Walzer et al., 2025). However, blockchain and distributed ledger technologies have emerged in other sectors as mechanisms to ensure traceability, immutability, and transparency of data across decentralized systems (Alotaibi et al., 2024). Their potential to address persistent traceability challenges in construction has been widely discussed, yet their relevance for biogenic carbon accounting remains largely unexplored. Further, improved traceability and verification are increasingly linked to the credibility of emerging green finance and carbon market instruments (Schletz et al., 2020).

Therefore, this paper adopts an exploratory perspective to investigate how blockchain-inspired system logics could support traceability and transparency of biogenic carbon in biobased construction materials, using bamboo as a representative case. Rather than proposing a finalized technical solution, the paper examines conceptual mismatches between current carbon accounting practices and material realities, and explores how distributed ledger principles could help bridge these gaps.

This study asks: *How can blockchain-inspired system principles be operationalised to guarantee traceable, auditable biogenic-carbon accounting across heterogeneous bamboo value-chains?*

Methods

The exploration follows a scoped and purposive analytical review suitable for an emerging research field, rather than a full systematic literature review. Relevant literature is selectively sampled to identify conceptual patterns and limitations in current biogenic carbon accounting practices, and the analysis is structured around three analytical steps:

(i) identification of traceability gaps in current biogenic carbon accounting practices,
(ii) abstraction of blockchain-relevant principles applicable to these gaps,

(iii) exploratory mapping of these principles onto bamboo-based material value chains,
(iv) formalization of these insights into a conceptual framework for traceable biogenic carbon accounting

First, common biogenic carbon accounting practices were reviewed with a focus on how carbon information is generated, aggregated, and transferred across life cycle stages. Particular attention was given to points where carbon attribution becomes ambiguous, such as material transformation, component assembly, reuse, and end-of-life treatment. This review was informed by existing LCA-based studies on bamboo construction materials and by current Environmental Product Declaration (EPD) and reporting conventions.

Second, blockchain technologies were not treated as a specific software implementation, but as a set of system principles. These include distributed state management, immutable transaction histories, unique identifiers, and rule-based state transitions. The analysis deliberately avoids technological specificity in order to focus on conceptual compatibility rather than implementation feasibility.

Third, bamboo-based construction materials were used as an exploratory case to test how these principles could be mapped onto real material flows. Bamboo value chains are characterized by biological growth phases, multiple processing steps, and a wide range of end-of-life scenarios. Conceptual data entities representing biogenic carbon quantities were defined and linked to material batches or components. Hypothetical life cycle events (such as processing, assembly, reuse, and disposal) were then interpreted as state transitions that would require transparent and verifiable updates of carbon information.

Fourth, the insights derived from the exploratory mapping were formalized into a conceptual framework for traceable biogenic carbon accounting. This step translates the identified system principles and observed material-flow dynamics into a structured entity–transaction model, in which biogenic carbon is represented as a persistent accounting state linked to material representations. Core conceptual elements, including Carbon Units, Material Tokens, and a defined set of life cycle transactions, were specified to capture how carbon information is created, transformed, transferred, and retired over time.

In addition, a set of invariants was introduced to ensure internal consistency, including conservation of carbon, single attribution, traceable aggregation, explicit state transitions, and auditable history. This formalization step consolidates the preceding analytical steps into a coherent system logic that can support transparent, continuous, and verifiable carbon accounting across heterogeneous value chains.

Results analysis and discussion

Review of current biogenic carbon accounting practices and points of ambiguity

Our ongoing analysis indicates that current biogenic carbon accounting practices are internally consistent within individual assessments, yet they exhibit structural limitations once carbon information is expected to remain traceable across multiple life cycle stages and actors. In most LCA-based studies on bamboo construction materials, biogenic carbon is quantified at the point of material production using established inventory data and is reported as an aggregated balance per functional unit (Tellnes et al., 2017). At this initial stage, carbon uptake and storage are clearly defined and methodologically unambiguous.

As materials progress through processing, assembly, and use phases, however, carbon information is progressively abstracted. Processing steps redistribute material mass through yield losses, residues, and by-products, but the associated carbon is commonly reallocated using averaging or allocation rules that do not preserve links to the original biomass source. During component assembly and at building level, carbon indicators are further aggregated into single values, which are suitable for comparative reporting but obscure the provenance and also the distribution of biogenic carbon within multi-material systems. In reuse scenarios, carbon storage is typically addressed through scenario-based assumptions rather than through documented continuity of material histories, while end-of-life treatments rely heavily on generalized modeling choices that are applied retrospectively (Silvia et al., 2025).

Dynamic life cycle assessment (LCA) has been increasingly explored to account for the temporal dynamics of biogenic carbon flows. However, existing approaches vary widely in their methodological choices, including system boundaries, time horizons, and modelling of carbon sequestration and release, reflecting a lack of consensus and leading to substantial variability in results (de Jong et al., 2026). This methodological diversity, together with increased data and modelling requirements, introduces additional complexity and challenges in interpretation (de Jong et al., 2026). While dynamic LCA can provide more temporally consistent representations in certain contexts, its added value remains case-dependent and it is not part of established standardized LCA practice, which today remains predominantly static. The contribution of this paper is complementary to this insight: rather than focusing on temporal modelling, it addresses the continuity and traceability of biogenic carbon across value chains.

These patterns reveal that biogenic carbon is repeatedly recalculated at successive system boundaries rather than transferred as a conserved and persistent quantity. While this approach aligns with the logic of conventional LCA, it limits transparency when carbon information is interpreted across parallel assessments or over extended time horizons. The resulting ambiguity is not primarily a consequence of missing data, but also of accounting structures that prioritize internal coherence over cross-stage continuity. As a result, attribution becomes increasingly dependent on assumptions embedded in models rather than on verifiable material trajectories.

Our findings suggest that the principal challenge in biogenic carbon accounting lies less in improving quantification methods and more in developing mechanisms that can preserve attribution, continuity, and auditability as materials move through complex value chains. Addressing this challenge requires system logic capable of explicitly managing carbon state transitions over time, which motivates the exploration of blockchain-inspired principles discussed in the following sections.

Blockchain-inspired system principles relevant to biogenic carbon traceability

Our analysis indicates that, when abstracted from specific software implementations, blockchain technologies can be understood as a set of system principles that directly address several of the structural weaknesses identified in current biogenic carbon accounting practices (Nair et al., 2024). When viewed through this lens, these principles show a high degree of conceptual compatibility with the traceability and transparency gaps discussed in the previous section.

We find that distributed state management is particularly relevant for biobased material value chains, where carbon-related information is generated, modified, and interpreted by multiple actors over time (Komdeur & Ingenbleek, 2021). In contrast to centralized databases or document-based reporting, a distributed state model allows all participants to reference a shared and consistent representation of carbon states. Importantly, this does not require full decentralization of governance or the absence of authoritative oversight. Rather, it ensures that updates to carbon information are synchronized across actors and assessment contexts, reducing the risk of divergent interpretations arising from parallel data silos.

Immutable transaction histories directly respond to the loss of provenance observed in conventional accounting workflows. In current LCA and EPD practices, carbon information is typically recalculated and overwritten as materials progress through successive life cycle stages. As a result, earlier assumptions and allocations are no longer accessible once new results are reported. By contrast, an immutable transaction logic preserves previous states while recording subsequent changes, enabling carbon information to remain auditable over time. This makes it possible to trace later interpretations (such as reuse or end-of-life outcomes) back to earlier decisions and methodological choices, rather than treating each assessment as an isolated snapshot in time.

Our analysis suggests that unique identifiers are a prerequisite for persistence. Assigning persistent identifiers to biogenic carbon quantities, rather than only to products, components, or documents, allows carbon information to remain associated with material flows even when physical elements are transformed, aggregated, or separated. This directly addresses the attribution loss observed during processing and component assembly, where carbon is currently redistributed through averaging and aggregation without preserving its original linkage to biomass sources.

Rule-based state transitions emerge as a further critical principle. In the reviewed accounting practices, decisions regarding carbon release, continued storage, or substitution effects are often embedded implicitly in scenario assumptions or applied retrospectively at reporting stages (He et al., 2024). Blockchain-inspired systems allow such decisions to be formalized as explicit rules governing state transitions. For example, conditions under which biogenic carbon remains stored, are transferred to a new use phase, or are considered released at end-of-life, can be defined and documented consistently. This shifts carbon accounting away from static reporting toward a dynamic, state-based representation that better reflects material trajectories over time.

Taken together, our results suggest that the relevance of blockchain technologies for biogenic carbon accounting lies less in automation or decentralization per se, and more in their capacity to formalize continuity, conservation, and transparency of carbon information, consistent with prior findings that digital construction technologies derive value primarily from decision support rather than from automation alone (Graser et al., 2021). By focusing on system logic rather than implementation, the proposed analysis illustrates how blockchain-inspired principles could complement existing LCA frameworks while addressing limitations that cannot be resolved through methodological refinement alone.

Exploratory mapping of blockchain principles onto bamboo-based material flows

Our exploratory mapping of the identified blockchain-inspired principles onto bamboo-based construction materials both illustrate the suitability and the constraints of these logics when confronted with real material flows. Bamboo value chains are particularly illustrative because they span biological growth, heterogeneous processing pathways, and highly variable use and end-of-life scenarios, which together expose where carbon information is currently lost, reinterpreted, or rendered non-verifiable. At the earliest stage, biogenic carbon is associated with biological growth in managed or semi-managed bamboo systems (Buonocore, 2023). In our mapping, this carbon is represented as a conceptual data entity linked to a defined biomass batch, for which uptake is temporally and spatially constrained. At this stage, the carbon state is relatively stable and attribution is comparatively unambiguous. Introducing a persistent identifier at this point enables the carbon quantity to remain referenceable independently of later transformations, thereby establishing a continuous accounting anchor across the subsequent value chain.

As bamboo undergoes processing such as cutting, splitting, flattening, or lamination, the physical material is divided into multiple output streams, including products, residues, and losses (Liu et al., 2024). Treating these steps as explicit state transitions makes the redistribution of biogenic carbon visible, rather than implicitly reallocating it through mass-based averaging. In our mapping, each processing event updates the carbon state by allocating portions of the original carbon entity to new identifiers associated with derived batches or components. This differs from conventional practice, where carbon is often reassigned at the level of the new product without preserving a traceable link to the originating biomass and the yield structure that produced it.

During component assembly, bamboo-derived elements are frequently combined with other biogenic and non-biogenic materials to form components and systems. In our framework, assembly is treated as a reversible aggregation of carbon entities rather than as a terminal reporting step. Carbon information remains linked to individual components even when aggregated for reporting purposes, preserving the option to disaggregate carbon states during selective disassembly, repair, or reconfiguration. This is particularly relevant for bamboo construction systems where replaceability and modular interventions are common, yet the carbon implications of partial replacement are difficult to represent within conventional building-level aggregation.

Reuse scenarios reveal an important advantage of the state-based approach: When a bamboo component is removed from its initial application and reintroduced elsewhere, conventional LCA practice typically represents this through scenario assumptions or crediting approaches that are external to the component's documented history. In our mapping, reuse is recorded as a state transition that extends the storage duration of the existing carbon entity. This avoids re-estimation and reduces the risk of re-claiming the same stored carbon across multiple assessments, while making reuse effects explicit, time-stamped, and auditable (Zea Escamilla et al., 2020).

End-of-life events further demonstrate the relevance of rule-based transitions. Disposal pathways such as incineration with or without energy recovery, landfilling, recycling, or cascading use represent qualitatively different carbon outcomes and are sensitive to timing. Our mapping shows that these end-of-life assumptions often dominate carbon conclusions, yet are rarely documented with sufficient granularity to be verifiable. Encoding end-of-life as a verifiable transition clarifies when and why biogenic carbon is considered released, substituted, or retained, and it links those outcomes to explicit events rather than to generic scenario choices applied after the fact.

Overall, the bamboo case indicates that blockchain-inspired principles can be meaningfully aligned with the material logic of biobased construction systems when life cycle events are represented as state transitions acting on persistent carbon entities. This approach makes allocations, assumptions, and boundary choices more transparent by externalizing them into recorded transitions. At the same time, our analysis suggests that the usefulness of such systems depends less on technological sophistication than on the clarity of the accounting rules, the definition of permissible transitions, and the governance mechanisms used to validate critical events, particularly those at origination and end-of-life.

Importantly, although the specific form of life cycle events such as end-of-life is not known in advance, their occurrence is inevitable. These events are treated as potential state transitions that are recorded as they occur, allowing carbon information to be updated incrementally rather than predefined through fixed scenarios.

Conceptual framework for traceable biogenic carbon accounting

Building on the ambiguities identified in current biogenic carbon accounting practices and our exploratory mapping of blockchain-inspired principles, we propose a conceptual framework intended to support traceable and transparent carbon accounting for biobased construction materials. The framework is not presented as a software architecture. Instead, we formalize a system logic that can complement LCA-based methods by preserving continuity of biogenic carbon information across life cycle stages, actors, and assessment contexts.

The central premise of the framework is that biogenic carbon should be treated as a persistent state associated with material flows, rather than as a static attribute recalculated at each assessment boundary. To operationalize this premise, we distinguish between (i) carbon information as a persistent accounting entity and (ii) physical material representation as a batch- or component-level entity. These are linked through explicit state transitions that correspond to life cycle events. In doing so, we aim to externalize allocation decisions and scenario assumptions into auditable updates rather than allowing them to remain implicit in isolated assessments.

At the core of the framework is a limited set of conceptual entities and transactions that define how biogenic carbon information is created, redistributed, transferred, and retired over time. Table 1 summarizes these elements.

Table 1: Conceptual entities and transactions in the proposed framework

Category	Concept	Description
Entity	Carbon Unit ($1\ tCO_2eq$)	Persistent representation of a quantified amount of biogenic carbon, including metadata on origin, material type, and data quality
Entity	Material Token	Representation of a physical material batch or component, referencing one or more Carbon Units
Transaction	Origination	Creation of Carbon Units associated with biomass growth and initial material production
Transaction	Transformation	Allocation, splitting, or aggregation of Carbon Units following material processing steps
Transaction	Assembly / Disassembly	Reversible aggregation or separation of Material Tokens without loss of carbon provenance
Transaction	Transfer of custody	Change of responsible actor while preserving carbon state and history
Transaction	End-of-life	Terminal or transformative update of Carbon Units reflecting release, substitution, or continued storage

Within this framework, life cycle events are interpreted as state transitions acting on Carbon Units rather than as opportunities for re-estimation. Processing steps redistribute carbon quantities explicitly by allocating portions of existing Carbon Units to derived Material Tokens. In the context of digital ledgers, a token is a cryptographically secured data object that represents a specific right, asset, or quantity and can be transferred, subdivided, and verified without a central intermediary (Marijana & Bernhard, 2025). Assembly aggregates material representation without erasing carbon provenance, thereby preserving the possibility of later disaggregation during repair, reuse, or selective dismantling. Reuse extends the storage duration of existing Carbon Units through documented transitions rather than through retrospective scenario reinterpretation. End-of-life events close or transform carbon states based on documented treatment pathways, making the timing and nature of carbon release or substitution explicit.

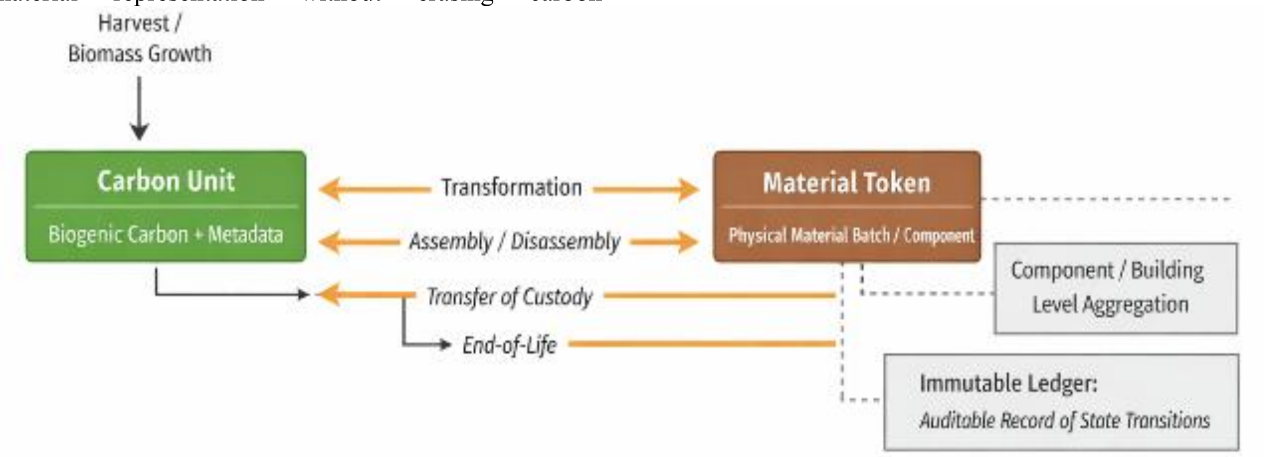

Figure 1: Conceptual entity–transaction diagram for traceable biogenic carbon accounting

To ensure internal consistency and prevent common accounting failures, we define a small set of invariants that govern all transactions (Knecht, 2025):

- First, conservation of carbon requires that the sum of biogenic carbon quantities across derived Carbon Units does not exceed the originating amount, except where methodological adjustments are explicitly recorded as such. This prevents the carbon leakage observed during processing and yield-loss allocation.
- Second, single attribution requires that a Carbon Unit can exist in only one active accounting state at a given time, preventing parallel claims on the same stored carbon. It therefore eliminates the double-counting risk highlighted when bamboo components are aggregated into downstream products.
- Third, traceable aggregation requires that aggregated indicators at component or building level are derived from referenced Carbon Units rather than entered independently. This addresses the loss of provenance that occurs when component-level data are rolled up to building-level totals.
- Fourth, explicit state transitions require that changes in carbon status (e.g., reuse, release, substitution) are represented as transactions rather than implicit assumptions. By doing so, it replaces the implicit scenario assumptions used for reuse and end-of-life modelling.
- Fifth, auditable history requires that state changes preserve previous states, enabling retrospective verification of carbon trajectories and the assumptions that shaped them. This provides the traceability needed to resolve the "black-box" recalculations typical of conventional LCA workflows.

The framework deliberately avoids prescribing specific technologies or governance models. Distributed ledger technologies are relevant insofar as they provide a shared, append-only record of state transitions across multiple actors, thereby supporting consistency and auditability in decentralized value chains. However, the conceptual contribution lies in formalizing continuity, accountability, and conservation of biogenic carbon information, rather than in decentralization or automation per se.

By framing biogenic carbon as a traceable state linked to material flows, the proposed framework addresses the transparency, double counting, and attribution challenges identified in the introduction. It also provides a structured basis for subsequent work on verification, governance, and integration with digital construction environments (for example, see Walzer et al., 2024), while remaining compatible with established LCA and EPD practices.

Figure 1 presents the framework as an entity–transaction system linking Carbon Units (persistent biogenic carbon states with metadata) to Material Tokens (physical batches or components).

Carbon Units are created at origination and persist throughout the system, while Material Tokens can be split, combined, assembled, or disassembled. Life cycle events are represented as transactions that update carbon states according to predefined rules while preserving an

auditable history. Aggregated carbon indicators are then derived from referenced Carbon Units rather than recalculated independently.
The diagram emphasizes conservation, explicit state transitions, and traceability across actors and life cycle stages, without prescribing a specific technological implementation.

Conclusions

Our objective in this paper was to explore how blockchain-inspired system principles could contribute to improved traceability and transparency of biogenic carbon accounting in biobased construction materials, with a particular focus on bamboo value chains. Rather than proposing a definitive technical solution, we set out to examine whether the structural challenges identified in current LCA- and EPD-based practices could be addressed through an alternative accounting logic that preserves continuity of carbon information across life cycle stages.
Our analysis shows that existing biogenic carbon accounting practices are effective for quantification within defined system boundaries but are limited when carbon information must remain attributable and verifiable as materials move through complex value chains. The review and discussion revealed that aggregation during processing and assembly, scenario-based treatment of reuse, and generic end-of-life assumptions progressively detach carbon indicators from their material origins. These limitations do not primarily stem from insufficient data or methodological inconsistency, but from accounting structures that repeatedly reinterpret carbon at successive assessment boundaries rather than transferring it as a conserved quantity.
By abstracting blockchain technologies into a set of system principles, we demonstrated that distributed state management, persistent identifiers, immutable transaction histories, and rule-based state transitions are conceptually well aligned with these challenges. When applied to bamboo-based material flows, these principles enable biogenic carbon to be represented as a persistent state linked to material batches and components and updated explicitly through documented life cycle events. The exploratory mapping showed that such an approach can make processing allocations, reuse effects, and end-of-life outcomes more transparent by externalizing assumptions that are otherwise embedded implicitly in conventional accounting models.
The conceptual framework proposed in this paper builds on these findings by formalizing biogenic carbon as a traceable accounting entity governed by a small set of invariants, including conservation, single attribution, and auditable history. In doing so, it outlines how a carbon ledger logic could complement existing LCA frameworks without replacing established standards. The potential of such a framework does not lie in automation or decentralization per se, but in its capacity to support consistent carbon attribution across actors and over time, thereby reducing the risk of double counting and increasing the credibility of carbon-related claims (Knecht & Stiller, 2023).
Our preliminary results suggest that ledger-based representations of biogenic carbon could provide a robust foundation for future carbon accounting and reporting mechanisms in the built environment. In particular, they offer a structured basis for component-level traceability, for handling reuse and cascading use scenarios, and for linking carbon outcomes to documented material trajectories rather than to abstract scenarios. At the same time, the exploratory nature of this work shows the need for further research on governance, verification, and integration with digital construction workflows, as well as on the institutional conditions under which such carbon ledgers could be adopted.
Overall, this study contributes to ongoing discussions on digitalization and sustainability in construction by reframing biogenic carbon accounting as a state-based, traceable process. By doing so, it opens a pathway toward carbon ledger approaches that can support transparent, verifiable, and scalable carbon accounting for biobased materials within and beyond the bamboo sector.

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