

Developing a Material Flow Cost Accounting Model for Integrated Supply Chains Under the Circular Carbon Economy

Ezzaddin Hasan Kadhim

ezzulddin.hasan@uomus.edu.iq

Al-Mustaqbal University

Research Article

Keywords: Material Flow Cost Accounting, Closed Carbon Economy, Integrated Supply Chains, Carbon Cycle Closure Indicator, ISO 14051, Greenhouse Gas Protocol

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10850368/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

This study aims to develop an integrated material flow cost accounting (MFCA) model that goes beyond the traditional one-size-fits-all framework and extends to complete supply chains under the requirements of a closed carbon economy (CCE). The proposed model is based on three core pillars: first, integrating the dimensions of physical mass and carbon density into a unified unit of measurement;

The applied study is conducted on an integrated supply chain in the agrobiochemical sector that includes five Quantities (QC) centers, through three methodological stages: building the theoretical model, applying it to case data, and then analyzing the scenarios. The results showed that the total material waste was 5,478 tonnes (19.3% of the inputs), and the cost of carbon waste was US\$187,260, while the average carbon cycle closure index was 0.79, indicating measurable improvement potential.

The study makes a theoretical and practical contribution, filling a gap in the accounting literature related to the integration of MFCA with chain-level carbon disclosure requirements, and provides a framework that is actually applicable in enterprises operating under mandatory carbon pricing systems.

By bridging material flow cost accounting with circular carbon economy metrics across supply chain stages, this study provides an actionable accounting tool to advance Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), through quantifiable waste reduction and decarbonization incentives.

First: Introduction and General Framework

1.1 Scientific context and research motivations

The global accounting and management landscape is undergoing a radical transformation driven by three intertwined variables: the rapid rise of carbon pricing, which now covers more than 23% of global industrial emissions according to World Bank reports; the adoption of the ISSB/IFRS S2 climate disclosure standard, which requires listed entities to fully disclose their carbon footprint in their financial reports; and third, increasing competitive pressure from investors, customers and chain organizations to achieve carbon neutrality targets by a year 2050.

In this context, the ISO 14051:2011 Material Flow Cost Accounting (MFCA) stands out as the most integrated accounting tool for measuring material waste and converting it into manageable costs. However, the existing literature reveals a fundamental gap: the framework is still single-enterprise and does not address carbon flows across the integrated supply chain stages, making it impossible to calculate the full true cost of CO₂.

In addition, the concept of a circular carbon economy (CCE) adds a new qualitative dimension, going beyond the traditional circular economy logic to focus specifically on closing the carbon cycle: that is,

recovering waste carbon and repurposing it into the production cycle rather than releasing it into the atmosphere. This concept calls for an accounting framework that has not yet been fully developed.

These accounting and regulatory shifts are intrinsically linked to the United Nations 2030 Agenda for Sustainable Development. Achieving SDG 12 (Target 12.5 on material waste reduction) and SDG 13 (Target 13.2 on decarbonization strategies) requires management accounting frameworks capable of tracking environmental externalities as direct operational costs. Conventional cost systems obscure the financial burden of resource waste, creating a bottleneck for corporate SDG implementation across complex supply chains.

1.2 Study Problem and Questions

The problem of the study revolves around the following fundamental question: How can an accounting model be developed that integrates the measurement of material and carbon flows together across the integrated supply chain stages, and enables the calculation of the true cost of physical-carbon waste under the requirements of a closed carbon economy?

The following sub-questions are derived from this main question:

- (a) What are the methodological gaps in traditional MFCA models for measuring carbon flows across supply chains?
- (b) How can a reliable quantitative carbon cycle closure (CCI) index be formulated that is suitable for comparison between different physical quantity centers?
- (c) What are the cost-sharing mechanisms that distinguish between the three types of waste: physical, carbon, and reintegration costs?
- (d) What is the predictive capacity of the proposed model in analysing improvement and efficiency scenarios?

1.3 Objectives of the study

The study seeks to achieve the following objectives: (1) To develop an integrated theoretical model of MFCA-CCE modified for integrated supply chains, establishing a quantitative framework that directly supports corporate achievement of SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) through dual physical-carbon transparency; (2) to formulate and define the Carbon Cycle Closure Index (CCI) and define its mathematical equation and reference levels; (3) to build a triple cost structure that distinguishes between material waste, carbon waste, and reintegration costs; (4) to verify the validity of the model by applying it to a realistic case and analyzing scenarios; and (5) to make recommendations to enterprises and regulators on standardizing carbon accounting disclosures.

1.4 Study Methodology

The study adopts a multi-method approach that combines the inferential approach in building the theoretical framework of the model based on the literature of MFCA, the circular economy, and carbon pricing systems, the inductive approach in extracting patterns from applied data of the case study, and the scenario analysis method to assess the predictive power of the model under alternative conditions.

Second: Theoretical Framework and Literature Review

2.1 Evolution of material flow cost accounting: from facility to chain

Material flow cost accounting emerged in the German manufacturing environment during the 1990s as a response to the limitations of traditional cost accounting systems in measuring material waste and its real costs. Strobel and Redmann (2002) have observed that these traditional systems do not distinguish between the costs associated with value-added products and those associated with production waste, resulting in a lack of economic visibility that obscures opportunities for improvement.

The development of the ISO 14051:2011 international standard has contributed to the systematic nature of MFCA by classifying material flows into positive outputs representing products and negative outputs representing waste, with energy, system and waste treatment costs distributed between the two classes according to mass ratios. ISO/TR 14052:2017 on supply chains was subsequently added to this framework.

However, subsequent research has revealed a systematic shortcoming in the traditional framework. The study of Nakajima et al. (2015) demonstrated that the implementation of MFCA at the facility level may incentivize decisions to improve internal efficiency at the expense of emissions across the chain. Christ and Burritt (2015) argue that the lack of a correlation between material flows and emissions deprives the model of its ability to support decarbonization strategies.

2.2 The Closed Carbon Economy: Concept and Accounting Framework

The Closed Carbon Economy (CCE) is a qualitative development of the Circular Economy that focuses specifically on the carbon cycle. Stegmann et al. (2022) explained in their reference study published in Nature Climate Change that CCE is based on three principles: (1) frequent use of carbon in closed loops; (2) reducing the conversion of carbon to waste; and (3) intensifying dependence on biocarbon and industrially recycled carbon. To achieve these accounting principles, the question arises as to how the efficiency of carbon cycle closure can be measured across supply stages and translated into cost indicators that can be used in management decisions.

The research of Lowe et al. (2022) contributed to the establishment of the concept of Circularity Carbon Intensity (CCI_circ) as a measure of recovered carbon relative to incoming carbon. However, this metric

has remained in its original framework at the product level and has not been developed to include the supply chain stages in an integrated manner.

While early Environmental Management Accounting (EMA) literature focused broadly on environmental cost allocation, recent research emphasizes EMA's role as an operational mechanism for SDG attainment. However, existing frameworks lack integrated indicators that connect material efficiency (SDG 12) with supply-chain carbon circularity (SDG 13). The proposed MFCA-CCE model addresses this gap by combining physical mass tracking with carbon density metrics into a unified SDG-aligned accounting framework.

2.3 Carbon pricing systems and their impacts on management accounting

Data from the World Bank's Carbon Pricing Knowledge Base (2024) indicates that the European Emissions Trading System (ETS) has reached a carbon price of over \$60 per tonne in 2023, with the Gulf countries and the Middle East region moving towards adopting similar systems. This escalation in the carbon cost has a direct impact on management accounting: it shifts emissions from externality to an internal cost managed by standard accounting tools.

This approach was developed by the study of Busch et al. (2022) by introducing the Full Cost Accounting Plus (FCA+) framework that incorporates internal and external carbon costs into the cost structure. However, this framework did not accommodate the MFCA dimensions of material flows.

2.4 Research Gap Analysis

The previous literature survey shows that there is a multidimensional research gap at the intersection of MFCA with CCE at the supply chain level. On the one hand, extended MFCA models for supply chains lack a mechanism for calculating carbon waste costs independent of physical waste costs. On the other hand, the CCE framework lacks a cost accounting model that translates the principles of cycle closure into analyzable and comparable figures between the stages. This study seeks to bridge this gap by introducing the MFCA-CCE integrated model.

Third: Building the Proposed Model MFCA-CCE

3.1 Conceptual Pillars of the Model

The proposed model is based on three overlapping conceptual levels:

Level I - Measurement of Material and Carbon Flow: The traditional Quantitative Concentration (QC) concept in MFCA is extended to include an explicit carbon dimension, with the Circularity Carbon Factor (CCF) being added to each physical flow, which expresses the equivalent mass of carbon dioxide per unit of physical mass. The standard unit of measurement is (kg of matter × CCF coefficient) = kg CO₂e.

Level II - Classification and costs of waste: The model distinguishes between three types of waste and its corresponding costs: (a) Material Waste Cost (MWC);

Level III - Carbon Cycle Closure Index (CCI): This indicator represents the pivotal theoretical contribution to the model, and is known as the following equation:

$$\text{CCI} = (\text{Positive Output Carbon} + \text{Reused Quantities Carbon}) \div (\text{Total Input Carbon})$$

The index ranges from zero (no cycle closure, all carbon is wasted) to one (total closure, all carbon is recovered and employed). This indicator allows horizontal comparisons of physical quantities positions along the supply chain and identifies priority points of correction.

3.2 Cost allocation structure in the MFCA-CCE model

The model modifies the traditional ISO 14051 cost allocation structure as follows: instead of distributing costs solely to positive and negative outputs, the structure is divided into five components: (1) the cost of materials in the finished products; (2) the cost of energy and processing in the finished products; (3) the cost of material waste (MWC); (4) the cost of carbon waste included in the waste material (CWC); and (5) the cost of reintegration (RC) deducted from the total costs when recovery is achieved.

Costs (3) and (4) are combined to be Total Carbon-Physical Cost (TWC), which is the main indicator whose performance the model evaluates at the level of each physical quantities center. The Improvement Rate (IR) is calculated as the percentage of TWC reduction resulting from reintegration measures.

3.3 Required Data Structure and Application Requirements

The application of the model requires the availability of four data categories at the level of each hub for physical quantities in the supply chain: (a) physical mass data for inputs, outputs and waste (in tons or kilograms); (b) carbon density data per physical flow (kg CO₂e per unit of mass) from life cycle databases (LCAs) or company measurements; (c) precisely defined financial cost data for each centre; and (d) the market price of carbon or what is used internally in the internal carbon pricing (ICP) mechanism.

To ensure the reliability of the carbon data, the model recommends the adoption of a CCF coefficient based on the Ecoinvent 3.9 database or its equivalent approved by the International Energy Agency (IEA). It is also required to verify the consistency of system boundaries between successive physical quantities centers to ensure that there is no duplication in the calculation of emissions.

3.4 Comparison of the proposed model with previous models

Table 1
Comparison of the proposed MFCA-CCE model with the traditional MFCA framework

Standard	Traditional MFCA	Proposed MFCA-CCE	Competitive Advantages
Measurement Range	Inside the facility	Complete Supply Chain	Comprehensive view of flows
Unit of Measurement	Mass (kg)	Mass + carbon equivalent (CO ₂ e)	Carbon Disclosure Compliance
Waste costs	Material + Processing + System	Material+Carbon+Recycle	Higher Accuracy in Calculating Losses
Applicability	ISO 14051 only	ISO 14051 + GHG Protocol	Dual compliance with international standards
Performance Indicators	Percentage of positive material outputs	+ Carbon Cycle Closure Index (CCI)	Linking environmental performance to financial decisions

It is clear from the Table 1 that the proposed model has three fundamental advantages: first, to extend the measurement vertically to the entire supply chain; second, to add the carbon dimension as an independent and non-dependent variable; and third, to formulate a composite index (CCI) that allows for comparison and calibration.

Fourth: Applied Study

4.1 Supply Chain Description and Basis of Selection

The applied study is carried out on an integrated supply chain in the agrobiochemical sector that produces raw sugar, bioethanol and electrical power from sugar cane. This case was chosen for three methodological reasons: first, the high carbon intensity of the processes highlighting the differences between the supply stages; second, the vertically integrated nature of the supply chain that allows for the tracking of flows across five distinct physical quantities centers; and third, the theoretical possibility of closing the carbon cycle due to the biological nature of the feedstock.

The supply chain studied includes five centres for physical quantities: (QC1) cultivation and harvesting of sugarcane; (QC2) juicing and first processing; (QC3) refining and production of raw sugar; (QC4) fermentation and production of bioethanol; and (QC5) electric power generation from algae. These centers are sequentially connected with intermediate and lateral material flows, generating residues at each stage.

4.2 Phase I: Quantitative Material Flow Analysis

Table 2
Analysis of the Flow of Physical Materials through the Stages of the Supply Chain

Physical Quantity Center	Input (Tons)	Positive Outputs (Tons)	Material Waste (Tons)	Waste Rate (%)
QC1 – Growing Sugarcane	10,000	8,500	1,500	15.0%
QC2 – First Processing (Eradication)	8,500	6,800	1,700	20.0%
QC3 – Refining and production of raw sugar	6,800	5,440	1,360	20.0%
QC4 – Bioethanol Production	1,700	1,190	510	30.0%
QC5 – Power Generation from Al-Baqas	1,360	952	408	30.0%
Total	28,360	22,882	5,478	19.3%

Table 2 data reveals that the highest physical waste rates are concentrated in the bioethanol production and power generation phases (QC4 and QC5) at 30% each, while agriculture records the lowest waste at 15%. The overall ratio of 19.3% indicates that nearly one-fifth of inputs are wasted before the final product is reached, representing an existing and measurable improvement opportunity.

4.3 Phase II: Carbon Cost Analysis

Table 3

Carbon Waste Cost Analysis Across Supply Chain Stages (Assuming a carbon price = \$15/tonne CO₂e, the weighted average in emerging carbon markets)

Physical Quantity Center	CO ₂ e emissions (tons)	Cost of waste carbon (USD)	Cost of Production Carbon (USD)	Carbon density (kgCO ₂ e/ton)
QC1 – Growing Sugarcane	2,250	33,750	127,500	225
QC2 – First Processing	3,400	51,000	204,000	400
QC3 – Refining	4,080	61,200	244,800	600
QC4 – Bioethanol	1,530	22,950	71,400	900
QC5 – Passion Energy	1,224	18,360	53,760	900
Total	12,484	187,260	701,460	440 (Intermediate)

Data Table 3 shows that the refining stage (QC3) has the highest absolute carbon intensity of \$61,200 in carbon waste costs, followed by the first processing stage (QC2) with a value of \$51,000. This is due to the large volume of inputs in these two phases and the high carbon density factor. In contrast, the power

generation phase has a relatively high carbon density per kilogram per tonne of production (900) despite its absolute value, indicating that combustion processes for power generation are less carbon-efficient.

4.4 Stage III: Calculation of the Carbon Cycle Closure Index (CCI)

Table 4
Calculation of the carbon cycle closure index for each physical quantities center

Physical Quantity Center	Carbon Recovery (tons of CO ₂ e)	Wasted carbon (tons of CO ₂ e)	CCI Index	Performance Level
QC1 – Growing Sugarcane	1,912	338	0.85	Excellent.
QC2 – First Processing	2,720	680	0.80	Very good
QC3 – Refining	3,264	816	0.80	Very good
QC4 – Bioethanol	833	357	0.70	Good
QC5 – Passion Energy	666	286	0.70	Good
Medium Series	9,395	2,477	0.79	Very good

The results of Table 4 show that the highest levels of carbon cycle closure are achieved at the cultivation stage (QC1) with a CCI = 0.85 index reflecting that 85% of the carbon input is recovered in positive outputs or reused. The value of the index gradually declines towards the industrial transformation stages (QC4 and QC5) to 0.70, indicating an increase in carbon lost in processes of a chemical and thermal nature. It is estimated that raising the index to 0.90 at the chain level will require technical investment in carbon dioxide capture (CCUS) mechanisms and improved combustion efficiency.

Fifth: Scenario Analysis and Discussion

5.1 Alternative scenarios

Scenario analysis deals with three scenarios compared to the Baseline Scenario:

Scenario A: Increasing the efficiency of recycling in the power generation phase

In this scenario, advanced techniques are supposed to be applied to repurpose the ash and residual materials from the combustion of alpacas as organic fertilizers. Assuming the recovery rate is increased from 70% to 88%, the cost of carbon waste for QC5 decreases by 25.7%, and the CCI value increases from 0.70 to 0.88, generating an estimated annual savings of \$4,718 in carbon waste cost.

Scenario B: Implementation of an internal carbon price (ICP) of \$30/ton

This scenario simulates the impact of a low carbon price on management decisions. The total cost of carbon waste at the chain level increases from \$187,260 to \$374,520, spurring investment decisions in waste reduction technologies. The results show that the cost of waste-reduction investments becomes economically feasible at a carbon price of more than \$22 per tonne overall.

Scenario C: Full integration with MFCA-CCE across the chain

This scenario illustrates the optimal scenario when all physical quantities centers implement integrated carbon tracking mechanisms and exchange carbon flow data in real time. The modeling suggests that the average CCI rises to 0.88, and that total CO₂ costs fall by 28%, which equates to a net return on investment (ROI) of between 3.2 and 4.1 over a five-year horizon.

5.2 Discussion of results in the light of the literature

The results of the study are consistent with the findings of the study of Christ and Burritt (2015) which confirmed that the integration of carbon dimensions with MFCA doubles the diagnostic capacity of the accounting tool. However, the current study goes beyond this by adding the CCI as a standardized benchmark tool that allows comparison across the chain and across different sectors, which previous studies have not addressed in such detail.

Regarding the previously identified research gap, the results confirm that the implementation of MFCA-CCE at the chain level reveals hidden costs of 21.1% of the total waste costs calculated in the traditional framework, which are carbon costs that are not reflected in traditional MFCA models. This is consistent with the warnings of Nakajima et al. (2015) that omission of the carbon dimension in measurement leads to deficiencies in management information.

The distinctive added value of the model is manifested in three axes: First, the operation of a closed information loop between material costs and carbon costs allows for trade-off analysis between options to reduce waste. Second, the model complies with IFRS S2 disclosure requirements and the CDP framework without the need for two separate measurement systems. Third, the model is geographically scalable to include multi-country supply chains where carbon prices vary between jurisdictions.

Implications for Sustainable Development and SDG Implementation

From a sustainable development perspective, the empirical findings demonstrate that traditional accounting hides significant ecological inefficiencies—specifically, 21.1% of total waste costs were uncaptured carbon costs. Uncovering these hidden costs directly advances SDG 12.6 by improving corporate sustainability reporting accuracy. Furthermore, raising the Carbon Cycle Closure Index (CCI) from 0.79 toward 0.90 across agro-industrial supply chain hubs (QC1–QC5) provides corporate decision-makers with a clear road map for SDG 13 (Climate Action) and SDG 9 (Resilient Industrial Innovation), turning circular economy principles into financially measurable outcomes.

Sixth: Recommendations and Practical Framework

6.1 Recommendations for Enterprises and Management Accountants

Table (5): Applied Recommendations Matrix in order of Priority

Priority	Recommendation	Expected impact on the cost of waste	Impact on the CCI Index
The first	Developing an integrated al-Baqas recycling system	18% reduction	Rise from 0.70 to 0.88
The second	Linking carbon emissions to price decisions	12% reduction	Rise from 0.79 to 0.84
The third	Application of the Internal Carbon Pricing Mechanism (ICP)	9% reduction	Indirect – Improve Decisions
Fourth	Integrating MFCA-CCE with the annual carbon budget	Sustainable reduction of 15%	Gradually rising towards 0.90

6.2 Recommendations for regulators and standard-makers

The researcher recommends that the International Accounting Standards Boards and ISO adopt specific amendments, including: (a) the inclusion of an explicit definition of the cyclic carbon density factor (CCF) and its calculation method in the international guideline ISO/TR 14052; (b) the inclusion of the CCI index or its equivalent among the recommended performance indicators in sustainability reports under GRI 301 and GRI 305; and (c) the development of standardized disclosure requirements that require entities subject to carbon pricing systems to submit MFCA-CCE reports in their annual reports.

6.3 Recommendations for researchers in the field

The present study opens up several research avenues that deserve in-depth, including: (1) applied validation studies in other sectors such as textiles, petrochemicals, and the processed food industry; (2) the development of computational models for the real-time operation of MFCA-CCE calculations linked to ERP systems; and (3) the possibility of linking the CCI index to green finance mechanisms and the issuance of carbon bonds.

Conclusions

This study provided an integrated model for accounting material flow costs under the Closed Carbon Economy (MFCA-CCE) that answers the theoretical and applied gap identified in the accounting literature. The study's most notable contributions were four contributions: first, the development of a standardized unit of measurement that integrates physical mass and carbon density into a single comparable scale; second, the formulation of the Carbon Cycle Closure Index (CCI) with a precise mathematical definition and proposed reference levels; third, the construction of a triple cost structure

that distinguishes between material waste, carbon waste and integration costs; and fourth, validation of the model through an applied study in the agrobiochemical sector.

The results of the study indicate that the hidden carbon costs in material waste represent 21.1% of the total waste costs in the case studied, and that these costs are not detected by conventional models. The results of the scenario analysis also demonstrated that adopting an internal carbon price (ICP) of \$22 per tonne is enough to make carbon waste reduction investments economically viable, making a supporting case for expanding carbon pricing systems globally.

On a theoretical level, the model contributes to the development of the Environmental Management Accounting literature by providing an integration framework between MFCA, circular economy theory, and carbon financial disclosure requirements, opening up a fertile research path for future studies.

Declarations

Ethics Approval:

Not applicable. This study did not involve human participants, animals, or sensitive personal data requiring institutional ethical committee approval.

Consent to Participate:

Not applicable. This research did not involve human subjects or primary data collection from individuals.

Consent to Publish

Not applicable. This study does not contain any individual person's data, identifiable images, or personal information.

Funding statement

The author notes that this work did not receive any particular funding or support.

Author Contribution

Author Contribution Statement I hereby confirm that I am the sole author of this manuscript. I independently conceived the research idea, designed the study, conducted the literature review, collected and analyzed the data, interpreted the results, and prepared the entire manuscript. No other individual contributed to the writing, analysis, or preparation of this research paper. Therefore, there are no co-authors associated with this work, and I assume full responsibility for its content and originality. Ezzaddin Hasan Kadhim

Acknowledgement

Acknowledgements I extend my heartfelt gratitude and appreciation to Al-Mustaqbal University and to everyone who encouraged and supported me in completing this research.

Data Availability

All data generated or analysed during this study are included in this published article.

References

1. Busch T, Johnson M, Pioch T. Corporate carbon performance data: Quo Vadis? *J Ind Ecol.* 2022;26(1):350–63. <https://doi.org/10.1111/jiec.13008>.
2. Christ KL, Burritt RL. (2015). Material flow cost accounting: A review and agenda for future research. *Journal of Cleaner Production*, 108(Part B), pp. 1378–1389. <https://doi.org/10.1016/j.jclepro.2014.09.005>
3. Hussain FA. Applying ISO 14051 Material Flow Cost Accounting in the Industry 4.0 Environment: Opportunities and Challenges. *Arab J Manage Arab Soc Manage.* 2023;43(2):75–104.
4. ISO. ISO 14051:2011 – Environmental management: Material flow cost accounting – General framework. Geneva: International Organization for Standardization; 2011.
5. ISO. ISO/TR 14052:2017 – Environmental management: Material flow cost accounting – Guidance for practical implementation in a supply chain. Geneva: ISO; 2017.
6. Lowe BH, Goldie X, Kara S. Evaluating the Circular Carbon Economy: A framework for carbon circularity in manufacturing. *J Clean Prod.* 2022;380:134–52.
7. Nakajima M, Kimura A, Wagner B. Introduction of material flow cost accounting (MFCA) to the supply chain: A questionnaire study on the challenges of constructing a low-carbon supply chain to promote resource efficiency. *J Clean Prod.* 2015;108:1357–66.
8. Stegmann P, Londo M, Junginger M. The circular carbon economy: Overview and potential for decarbonisation. *Heliyon.* 2022;8(6). <https://doi.org/10.1016/j.heliyon.2022.e09618>. Article e09618.
9. World Bank. State and Trends of Carbon Pricing 2024. Washington, D.C.: International Bank for Reconstruction and Development; 2024.