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A Methodology for Evaluating Economic–Environmental–Social Sustainability

Elena Fregonara, Francesca Thiebat, Chiara Senatore *, Mónica Alexandra Muñoz Veloza, Alice Masoero, Roberto Giordano and Diego G. Ferrando

Architecture and Design Department, Politecnico di Torino, 10129 Turin, Italy; elena.fregonara@polito.it (E.F.); francesca.thiebat@polito.it (F.T.); monica.munozveloza@polito.it (M.A.M.V.); alice.masoero@polito.it (A.M.); roberto.giordano@polito.it (R.G.); diego.ferrando@polito.it (D.G.F.)

* Correspondence: chiara.senatore@polito.it

Abstract

This paper builds on research from a project aimed at promoting the circular economy through processes based on low-impact materials derived from natural fibers. A methodology is developed to assess the economic, environmental, and social sustainability of alternative production scenarios, thereby supporting the ranking of options. Assuming the principles of Life Cycle Thinking and circular economy and the operational aspects of Life Cycle Costing (LCC), Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) approaches normed by international standards, an integrated approach is proposed based on the construction of a joint Global Cost indicator. Attention is paid to harmonizing impacts assessed in their own units of measurement to arrive at a monetary indicator for summarizing and simplifying the prioritization of alternatives. As a result, the integrated Global Cost calculation methodology is presented to internalize social and environmental impacts, as well as economic ones, and to evaluate the sustainability of materials derived from primary and waste natural fibers.

Keywords: sustainable development goals; circular economy; life cycle costing; life cycle assessment; social life cycle assessment; joint Global Cost; discounted cash flow analysis; sustainable architecture; life cycle design; natural fibers

1. Introduction

Reducing the environmental impacts of production across various economic sectors is currently of primary importance to combat climate change. The transition to circular economic and production models is also guided by the international and European regulatory frameworks and their related objectives. These include the targets set by the European Parliament on the climate emergency (2019/2930(RSP)), specifically a 55% reduction in emissions by 2030 and climate neutrality by 2050, as regulated by the European Climate Law (Regulation 2021/1119) and by the Circular Economy Action Plan (COM 98, 2020).

That said, reusing and recycling waste, as well as reducing it, are key elements in developing sustainable production processes [1–3]. These key elements also serve as a means of valorizing resources, reducing negative environmental externalities, promoting circular production models, and strengthening relevant market segments [4,5]. This is even more true for production chains based on natural and local raw materials [6].

From a methodological perspective, the use of life cycle approaches is crucial for assessing the efficiency of circular processes and products [7,8]. Likewise, adopting a

Academic Editors: Luisa Sturiale and Maria Rosa Trovato

Received: 30 January 2026
Revised: 22 February 2026
Accepted: 25 February 2026
Published: 27 February 2026

systemic vision is crucial for enhancing resource management, achieving sustainable goals, and mitigating environmental impacts. Moreover, it promotes the implementation of sustainable and circular practices, as well as resilient, innovative, and socially responsible business models. The research carried out within the Circular Design for Natural Fibers (CD4NF) project, which was included in the "Made in Italy Circolare e Sostenibile (MICS)" Extended Partnership, part of Next Generation EU and funded by the National Recovery and Resilience Plan, is developed on these premises.

In particular, the research group from the Department of Architecture and Design at Politecnico di Torino, which participated in the project alongside other groups from universities nationwide, has focused on natural fibers. Specifically, the research group focused on by-products of local production chains (in Italy) and on virgin fibers derived from traditional Italian crops, such as hemp, nettle, and bamboo.

Within this context, the paper aims to illustrate the methodological framework developed for assessing the overall sustainability of natural fibers in design and architecture. It is based on a joint indicator calculation for evaluating materials and products derived from primary natural fibers and/or scraps (waste and by-products) from Italian cultivation and production supply chains.

This paper is organized as follows. Section 2 describes the research workflow adopted within the CD4NF research project. Section 3 focuses on synthesizing the literature background and regulatory framework. Section 4 illustrates the methodological framework as the primary research outcome. Sections 5 and 6 concludes the work.

2. The Research Workflow

The research is based on the principles of Life Cycle Thinking. The methodology adopted focuses on Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), as well as related measurable indicators.

Specifically, the methodology can be adopted to measure the overall performance of production chains across various sectors. Nevertheless, the research experience developed within the CD4NF project focuses on natural fibers for architecture and design, with a specific emphasis on bamboo cultivation. The latter was selected as a case study for experimental testing of the methodology. Specific data and results from the bamboo analysis will be the focus of a subsequent paper.

Figure 1 presents a graphical synthesis of the research workflow.

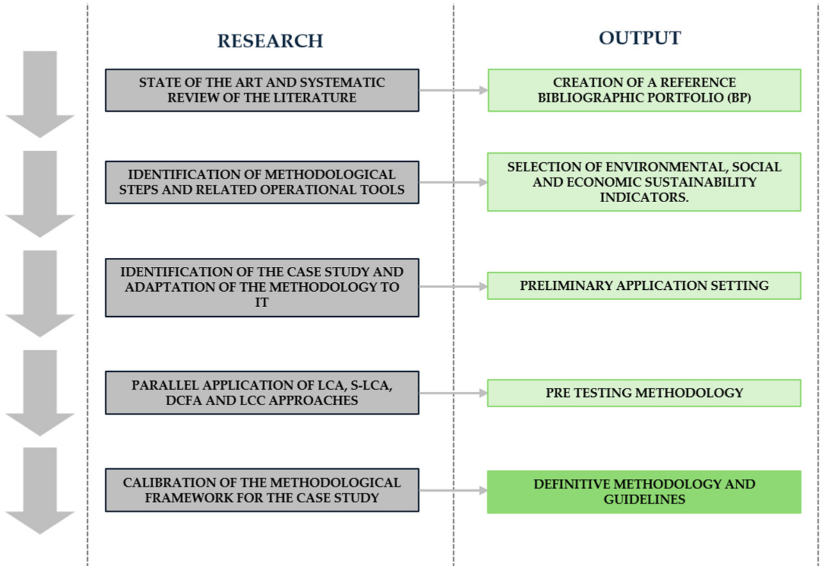

Figure 1. The research workflow (source: authors' elaboration).

The research analyzed the state of the art through a systematic review of international scientific literature. The goal was to identify approaches for assessing sustainability and their areas of application. The focus was on production chains, circular processes, and integrations between LCA, LCC, and S-LCA to select the most suitable approaches for assessing the overall sustainability of natural fibrous materials. Concretely, the authors [9] have outlined and discussed the literature analysis, resulting in a reference Bibliographic Portfolio (PB) that was useful for identifying the most consolidated approaches within the context of natural fibers.

Starting from the literature, methodological references and related operational tools for integrated assessment were identified. This phase led to the selection of sustainability indicators, which served as the basis for the subsequent development of the application.

A reference case study was identified, and a preliminary application setting was conducted, supported by specific indicators for each sustainability dimension applicable to the real context, also drawing on databases and technical literature.

The first methodological framework was tested in the case study by applying the approaches in parallel. This allowed for an initial simulation to be conducted.

Finally, the methodological framework for the case study was calibrated. Specifically, this was achieved by calculating the joint Global Cost indicator and simultaneously verifying the applied models. This allowed the authors to validate the framework and define the final guidelines as the research's output.

3. Literature Background and Regulatory Framework

Within this research project, a systematic review of the state of the art was conducted to explore the interactions among methods used to assess the sustainability of natural fibers [9]. The literature review was performed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [10].

The initial search yielded 787 publications covering the period 2005–2026. After the screening process, 110 records were selected, including peer-reviewed journal articles and conference proceedings. Nevertheless, among the 110 selected studies, only four addressed all three dimensions of sustainability. Twenty publications jointly examined environmental and economic aspects, while studies focusing on a single dimension were primarily dominated by Life Cycle Assessment (LCA) approaches (n = 102), with only one study each employing Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). To facilitate the interpretation of the results, a graphical analysis was performed using VOSviewer 1.6.19, developed by Leiden University (Figure 2).

An in-depth examination of 43 case studies across the building, civil engineering, and design sectors reveals that sustainability assessments of natural fibers primarily rely on CO_2-equivalent indicators to evaluate environmental performance. Economic evaluations mainly employ Payback Period and Net Present Value, whereas social dimensions are typically assessed using the PSILCA database.

Studies that address the integration of life cycle approaches exhibit two methodological orientations:

- Combined approaches within a single analytical framework.
  These contributions are primarily limited to theoretical assessments or simulation-based models. They are mainly applied in the sectors of food [11,12], biofuels [13,14], chemicals [15], and construction and design [16–18]. They do not systematically integrate economic, environmental, and social dimensions.
- Parallel approaches.
  In these studies, LCA and LCC are conducted separately and subsequently compared.

Studies are mainly applied to biofuel and waste treatment [19–23], construction [24–30] and the agri-food sector [31].

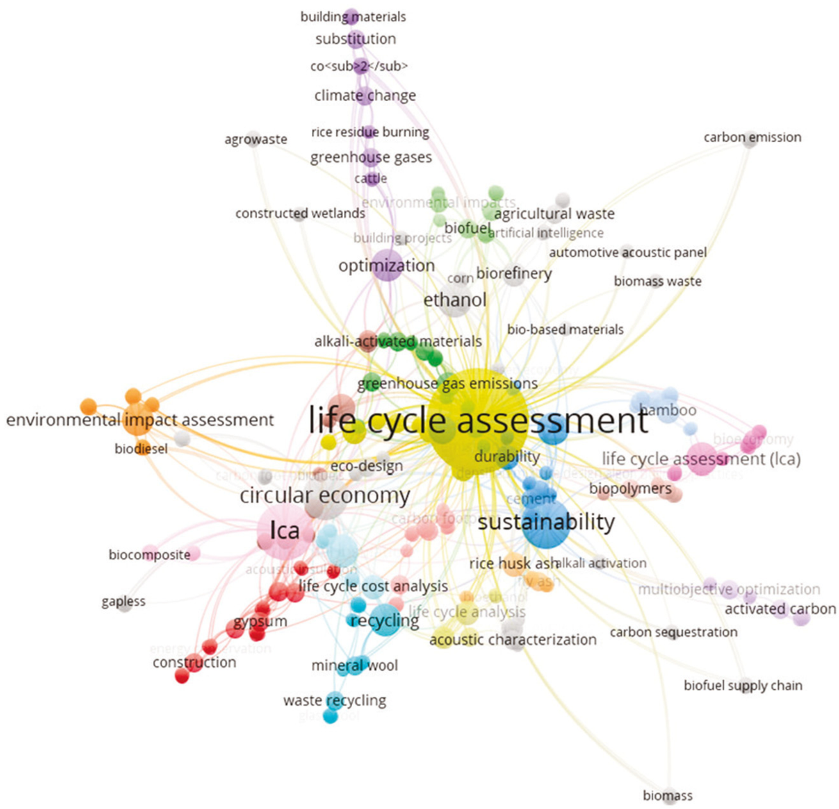

Figure 2. Keyword mapping performed using VOSviewer software (Source: authors' elaboration).

The findings of the systematic review indicate that the sustainability assessment of natural fibers in the construction sector is extensively covered in the literature and broadly consistent with European policy objectives. Nevertheless, despite the prominence of the three sustainability dimensions in national and international agendas, their translation into metrics and regulatory instruments remains underdeveloped.

Furthermore, the analysis of scientific literature highlighted the predominance of the LCA approach, adopted in almost all studies and, in some cases, integrated with the LCC approach. The use of the S-LCA approach, however, appears limited to a small number of contributions. The emerging evidence also reveals a high degree of variability in functional units, impact indicators, and databases used, suggesting the need for methodological harmonization to improve the comparability and replicability of studies.

Overall, the review highlights the rapid growth in scientific output and the growing interest in circular economy practices and resource valorization. However, a significant imbalance persists across the dimensions of sustainability: while the environmental component is largely consolidated, the economic and, especially, the social aspects remain marginal. This asymmetry indicates priority research areas for developing truly integrated life cycle approaches.

In addition to the systematic review described above, the relevant standards were outlined.

The European regulatory framework for environmental, economic, and social sustainability is complex and encompasses measures that promote the use of various approaches based on the principles of "Life Cycle Thinking". Regarding the environmental dimension and, specifically, Life Cycle Assessment (LCA), the primary methodological references are the ISO 14040:2021 [32] and ISO 14044:2021 [33] standards, which define the principles, framework, requirements, and guidelines for conducting LCA studies applicable to products, services, and, through specific sector standards, buildings and construction works [32,33].

At the product and service scale, a series of European instruments and technical standards support and operationalize the use of LCA results. Among the main tools are the EU Eco-label (Reg. EU 66/2010) [34], which is based on a life cycle perspective for selected product groups, and Environmental Product Declarations (EPDs), governed by UNI EN ISO 14025:2010 [35], which provide Type III environmental declarations for products using LCA-based indicators. For construction products, UNI EN 15804:2021 [36] specifies product category rules and impact categories to be reported in EPDs, ensuring comparability across alternative solutions. At the building scale, the UNI EN 15978:2011 [37] and UNI EN 17472:2022 [38] standards define the framework for assessing the environmental performance of buildings throughout their life cycle and for evaluating economic performance by accounting for investment, operation, and life cycle, structuring the analysis into standardized life cycle stages (production, use, end-of-life, and beyond-the-life-cycle benefits and loads) [37,38]. This ensures consistency between building-level LCA and product-level EPDs.

Such a regulatory framework also supports the application of Life Cycle Costing (LCC), which extends the life cycle perspective to economic performance by accounting for investment, operations, maintenance, and end-of-life costs over the reference service life. In the construction sector, this perspective aligns with standards such as ISO 15686-5:2017 [39], UNI EN 15978-1:2011 [37], and EN 15459:2007 [40] on Life Cycle Costing for buildings and constructed assets, as well as with European policy instruments that promote the integration of economic and environmental criteria in decision-making.

For the social dimension, the Social Life Cycle Assessment (S-LCA), recently standardized in ISO 14075:2024 [41], is primarily applied in sector-specific initiatives and voluntary schemes that develop indicators and data-collection protocols at the supply chain level. These initiatives build on guidelines developed within the UNEP/SETAC Life Cycle Initiative and contribute to the progressive consolidation of S-LCA practice across various industrial sectors [42,43].

Finally, Life Cycle Sustainability Assessment (LCSA), as outlined in the UNEP/SETAC report "Towards a Life Cycle Sustainability Assessment", provides the overarching conceptual framework that integrates LCA, LCC, and S-LCA results into a coherent decision-support perspective [44]. In this sense, the European regulatory and standardization landscape—from product and building-level LCA standards to instruments such as Green Public Procurement (GPP), the EMAS environmental management scheme, and sectoral initiatives on social and economic performance—creates an enabling environment for the development and application of integrated life cycle-based assessment methods such as the one proposed in this study [45]. This research also considers the standard UNI EN 17472:2022 [38], which sets out the requirements and specific methods for assessing the environmental, economic, and social performance of civil engineering works.

4. Methodological Framework: A Proposal to Evaluate the Material and Product Sustainability

Given the evolving regulatory and market framework, and considering the importance of integrating environmental, economic, and social sustainability indicators into production processes, the authors have developed a methodological framework aligned with the main goals of the CD4NF research project, providing a tool for assessing and comparing products and systems in the design and construction sector. The framework has been divided into five main steps, as illustrated in Figure 3, and is intended for researchers and design consultants. The proposed steps allow the method to be applied in various contexts while maintaining scientific coherence and comparability of the results. Furthermore, the framework enables effective communication and sharing of the outcomes with stakeholders.

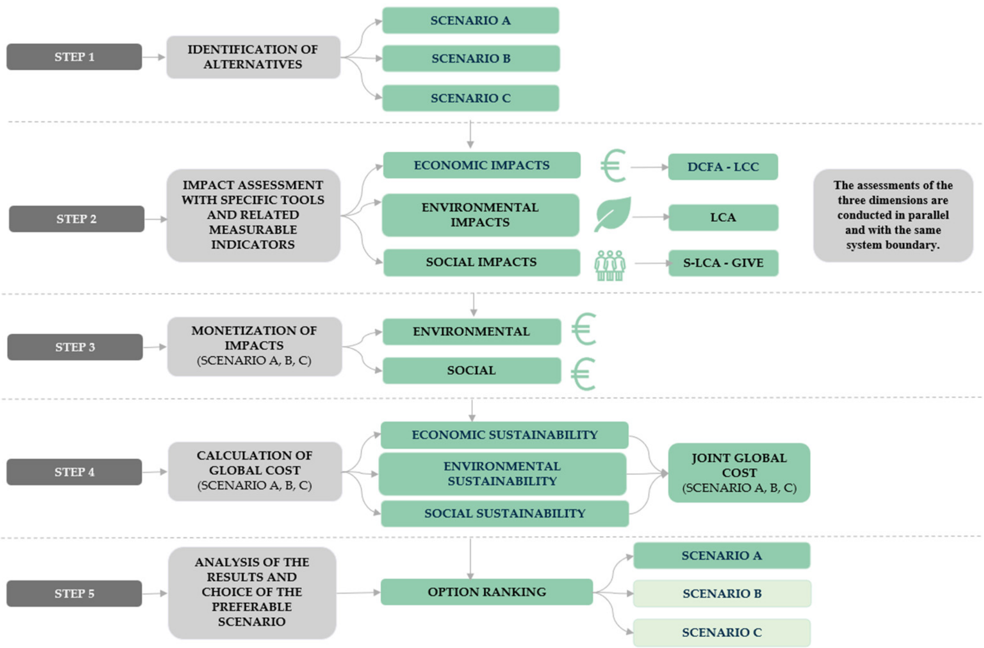

Figure 3. The methodological framework's workflow (source: authors' elaboration).

This section provides a step-by-step guideline to support research and design teams in applying the methodological framework to evaluate the most multidimensionally sustainable option.

4.1. Step 1—Alternative Options Definition

The first step is to define the alternative scenarios to be evaluated. They may represent different design options, technologies, management strategies, or operational configurations of a product or process. The scenario selection is based on technical, scientific, regulatory, and strategic criteria, with consideration of the study's objectives and the stakeholders involved. Each scenario is described through technical parameters, process inputs/outputs, and quantitative and qualitative data relevant to the subsequent evaluation steps. Since the quality and robustness of the entire process largely depend on the definition of the initial scenarios, a rigorous characterization ensures that the comparison between alternatives facilitates the identification of the most sustainable option.

This first step, in turn, involves four operational phases, described in Figure 4.

The first phase of Step 1 consists of one or more introductory meetings between a pool of researchers/consultants and interested stakeholders (e.g., company and technical stakeholders) to define the study's objective. The aim is to outline the study's scope, including the functional unit, service life, life cycle stages to be considered, system boundaries, indicators to be calculated, and the required level of detail. It is advisable to assume the exact system boundaries and functional units for all three evaluation approaches (LCA, LCC, and S-LCA) as suggested by Ref. [46]. This first phase is based on the reference LCA standard [32]. Figure 5 represents the life cycle stages of a product structured according to the LCA approach and the UNI EN 15978:2011 standard [37].

In detail, the stages are structured as follows: production (A1–A3): includes the cultivation and harvesting of natural fibers (i.e., sheep wool) (A1), transport to the processing facility (A2), and pre-processing and manufacturing of materials and products

(A3). This stage generates not only the main products but also by-products and waste that can be reintroduced into the production cycle or disposed; transport and installation (A4–A5): the product is transported to the construction site following the cultivation and harvesting of natural fibers (i.e., sheep wool) (A1). This involves transport to the n site (A4), installation (A5), and the possible production of waste; use (B1–B7): the product may undergo maintenance (B2), repair (B3) or replacement (B4), generating waste and end-of-life products; end-of-life (C1–C4): includes demolition (C1), waste transport (C2), waste treatment (C3) and final disposal (C4); and benefits and burdens beyond the life cycle (D): this stage considers the reuse, recycling and recovery of materials, reducing the overall environmental impact.

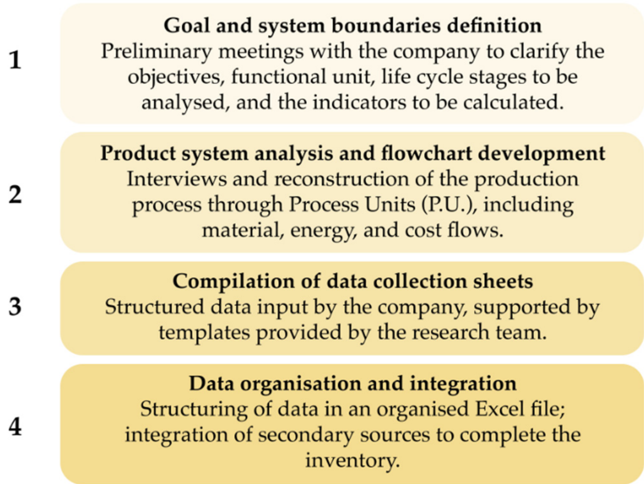

Figure 4. A synthesis of the four operative phases in the Step 1—"Alternative Options Definition" (source: authors' elaboration).

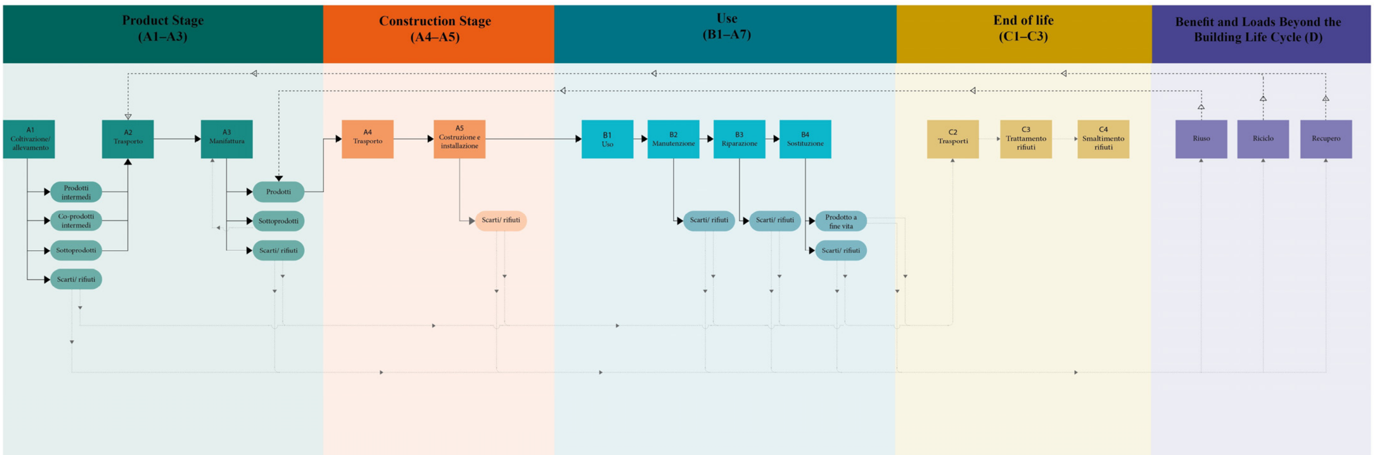

Figure 5. A product's life cycle stages and the connection between processes [37] (source: authors' elaboration).

In the second phase of Step 1, interviews with company and technical stakeholders are crucial for defining the production process and the supply chain. The collected data is organized into a flowchart divided into Unit Processes (U.P.) that represent the various activities carried out within the life cycle and identified within the system boundaries, such as the material and energy flows, the workers employed, and the cost of components, both direct and indirect, with reference to the identified economic cycle. Figure 6 shows a production system divided into sample macro-Unit Processes (Macro U.P. B and C), each composed of multiple U.P. Within the system boundaries, the incoming (input) and outgoing (output) flows of materials, energy, costs, and workers are highlighted.

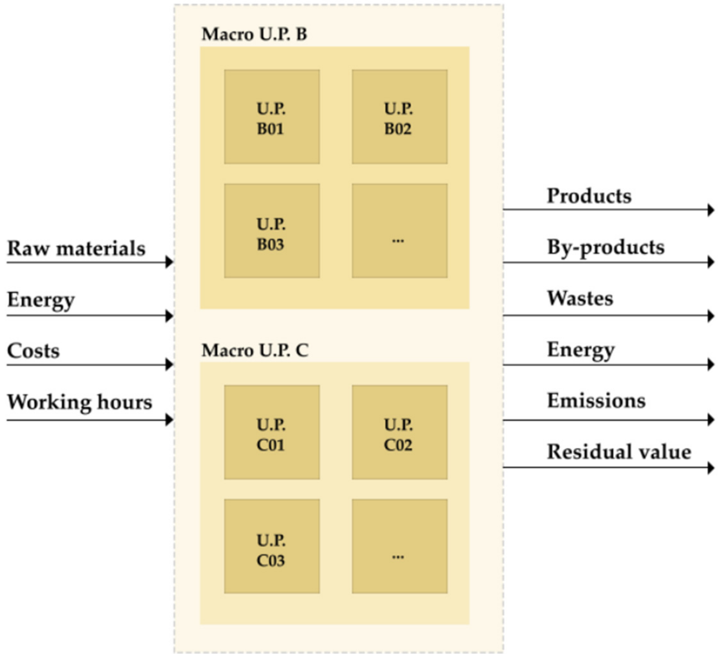

Figure 6. Input/output flow within the production system boundaries (source: authors' elaboration).

In the third phase of Step 1, the company and technical stakeholders complete the data collection forms provided by the researchers, which are designed to facilitate structured data entry. These forms can be adapted to suit the specific product type and supply chain, as well as the available data. They are a flow analysis tool for production processes, helping collect data on materials, energy, water, transportation, and labor used in manufacturing. Each form is divided into input and output categories, described with units of measurement, quantity, cost, and data source (direct or estimated).

In the last phase of Step 1, the stakeholders organize the collected direct data in spreadsheet files, integrating, where necessary, data from secondary sources (e.g., environmental databases, scientific literature, statistical or technical data, and price lists) to fill in any gaps.

Figure 7 provides an example showing the data collection structure for Unit Process (U.P.) analysis, broken down by year, macro-Unit Processes (Macro U.P.), Unit Processes (U.P.), and dataset. Furthermore, detailed information is provided on the type of activity (e.g., supply or installation) and various dimensional specifications of the materials used.

4.2. Step 2—Impact Assessment with Specific Tools and Measurable Indicators

Based on the data collected in Step 1, the second step of the methodology applies parallel approaches to calculate environmental, social, and economic impacts using specific analysis tools such as SimaPro v.9.2.0.2 for LCA, Excel spreadsheets for LCC, and S-LCA spreadsheets, all while maintaining the exact system boundaries for the three sustainable dimensions.

The following paragraphs outline the operational phases for applying the approaches to assess environmental, social, and economic impacts.

Environmental impact assessment

Life Cycle Assessment (LCA) is the internationally recognized method for assessing the environmental impacts of systems, processes, or products. In this framework, the Life Cycle Assessment of the alternative options was performed using SimaPro in accordance with the principles and requirements defined by ISO 14040:2021 [32] and ISO 14044:2021 [33], and consistent with the recommendations of the International Reference Life Cycle Data System Guide (ILCD) promoted by the Joint Research Centre (JRC) of the European Commission.

Input									
Year	**Macro U.P.**	**U.P.**	**Dataset**	**Description**	**Type**	**Width [m]**	**Height [m]**	**Diameter [m]**	**...**
Anno X	**B**	**B01**			**Supply**				
					Installation				
		B02			**Supply**				
					Installation				
		B...			**Supply**				
					Installation				
Anno XX	**B**	**B01**			**Supply**				
					Installation				
	C	**C01**			**Supply**				
					Installation				
		C...			**Supply**				
					Installation				

Figure 7. Example of a data collection spreadsheet (Source: authors' elaboration).

Based on the standard assumptions defined in Step 1—i.e., functional unit(s), system boundaries, reference service life, and life cycle stages considered—the LCA is articulated into the following operational phases.

Life Cycle Inventory (LCI)

The inventory compiles and structures the data collected in Step 1 for each product system based on natural fibers and/or agro-industrial by-products. Primary data include information obtained directly from the company and technical stakeholders (e.g., process parameters, material and energy inputs, yields, waste and by-product streams). Secondary data, drawn from internationally recognized databases integrated into SimaPro, such as Ecoinvent and Agri-footprint, are used to complete the inventory when primary data are not available or to represent upstream and background processes.

Unit Processes (U.P.) modeling

The product system is represented as a network of Unit Processes that describe the relevant elementary processes within the system boundaries (e.g., cultivation or collection of primary fibers, pre-treatment and processing steps, transport, manufacturing, and end-of-life operations). For each U.P., input flows of materials and energy and output flows of products, co-products, emissions, and waste are specified. Depending on the case study, the model can be articulated by time steps (e.g., annual operations for cultivation systems) and/or by life cycle stage, consistent with the choices and assumptions made in Step 1. Before moving to the impact calculation, an internal consistency check is performed to verify the model's mass and energy balance, as a prerequisite for robust subsequent analyses.

Life Cycle Impact Calculation and Indicator Selection

This phase converts LCI results into impact indicators by assigning elementary flows to the selected impact category(s) and applying the corresponding characterization factors implemented in SimaPro. In line with the objectives of the integrated framework, particular attention is paid to the climate change category and to the quantification of greenhouse gas emissions, expressed both as CO_2 and as CO_2 equivalents (e.g., kg CO_2-eq per functional unit). These indicators constitute the environmental input used in the subsequent monetization phase (Step 3) and in the calculation of the joint Global Cost indicator. The methodology remains open to the calculation of additional impact categories when required by the specific application.

Interpretation of results

The interpretation phase analyses the LCA outcomes in relation to the goal and scope defined in Step 1 and to the overall integrated framework. It includes checks on data quality and completeness, cautions on data completeness, identification of key environmental hotspots throughout the life cycle, and a discussion of assumptions and criticalities. The LCA results are then synthesized in a form suitable for comparison between alternative options and for their integration with social (S-LCA) and economic (LCC/DCFA) results, as well as within the joint Global Cost indicator, in line with the principles and requirements of ISO 14040:2021 [32] and ISO 14044:2021 [33].

Social impact assessment

The assessment of social sustainability is based on the Social Life Cycle Assessment (S-LCA) approach and follows a methodology structured into five key phases:

- Selection of stakeholder categories;
- Selection of the impact assessment method;
- Definition of social subcategories;
- Definition of inventory indicators;
- Definition of Reference Scales and Performance Reference Points (PRPs).

The methodological approach adopted aligns with UNEP [43] guidelines and integrates contributions from consolidated sources, including the UNEP Methodological Sheets [47], the PSILCA database, and the Product Social Impact Assessment (PSIA) Handbook [48], which represent the most advanced references currently available for social impact metrics.

The stakeholder categories considered include workers, local communities, society at large, consumers, and value chain actors, selected based on system boundaries and the analysis objectives.

The definition of social subcategories is based on a materiality assessment that combines the relevance stakeholders attribute with the research team's evaluation. Only subcategories that exceed a predetermined joint threshold of significance (materiality) are retained, ensuring that the analysis focuses on social aspects genuinely pertinent to the system under study. The subsequent identification of inventory indicators relies on a systematic comparison of key bibliographic and methodological sources, ensuring coherence, comparability, and adequacy with respect to the selected subcategories. Although most social impact indicators are applicable across sectors and product systems, studies on bio-based materials primarily address diffuse, poverty-related social risks embedded in agricultural supply chains, whereas studies on petrochemical and non-bio-based materials frequently focus on concentrated, industrial, and hazard-related risks [49]. Indicators can be specific (based on primary data referring to the case study) or generic (based on secondary data referring to sectoral or territorial contexts).

Consistent with the most recent scientific literature, this study adopts the "Reference Scale" Type I S-LCIA approach, which is considered more mature, better documented, and better developed than the impact-pathway-based model (Type II S-LCIA), whose applicability remains limited.

The Reference Scales, developed for each indicator, consist of five ordinal levels ranging from −2 to +2, each associated with a Performance Reference Point derived from international standards, legal requirements, sectoral best practices, or other authoritative sources. The comparison between collected data and scale levels enables characterization of the social performance of system components, highlighting both positive contributions and potential social risks (Figure 8).

Scale Level	Description
+2	Ideal performance. Best in class
+1	Beyond compliance
0	Compliance with local and international laws and/or basic societal expectations
−1	Slightly below compliance level
−2	Starkly below compliance level

Figure 8. Generic scale with 5 levels for social inventory indicators (Source: authors' elaboration from (p. 83, [43])).

Although S-LCA provides qualitative, semi-quantitative, and in some cases quantitative assessments of social impacts, it does not include their monetization. To address this gap and incorporate the social costs of greenhouse gas (GHG) emissions into the joint Global Cost calculation, economic values estimated through the model developed by Rennet [50] were employed.

Greenhouse Gas Impact Value Estimator (GIVE)

The study by Rennet [50] provides a structural reassessment of the Social Cost of Carbon Dioxide (SC-CO_2) through the development of the integrated GIVE model (Greenhouse Gas Impact Value Estimator), designed to quantify in monetary terms the societal damages associated with the emission of one ton of CO_2. The model systematically incorporates climate-related effects on mortality, agricultural productivity, building energy demand, and coastal risks, and rigorously considers the discount rate—an essential element for evaluating intergenerational impacts, given the long atmospheric lifetime of CO_2.

The authors estimate a mean SC-CO_2 value of 185 \$/tCO_2 (base year 2020, 2% discount rate), more than three times higher than the current official U.S. estimate. Mortality impacts represent the most significant contribution (90 \$/tCO_2), followed by losses in agricultural productivity (84 \$/tCO_2), while effects on energy demand (9 \$/tCO_2) and sea-level rise damages (2 \$/tCO_2) contribute to a lesser extent. By integrating these components, the GIVE model delivers a more comprehensive and methodologically robust estimate, consistent with welfare economics principles, and provides an updated and coherent representation of the socioeconomic impacts associated with climate-altering emissions [50].

Economic impacts evaluation

Financial feasibility and economic sustainability analyses are crucial components in supporting strategic decisions aimed at efficiency, replicability, and long-term sustainability [51]. They are developed using discounted cash flow analysis (DCF) and the LCC approach, respectively.

For consistency, both DCFA and LCC adopt the same system boundary and time horizon already defined for environmental (LCA) and social (S-LCA) assessments. This enables the development of an integrated analysis, facilitating a comparative interpretation of the results and identifying the most sustainable alternative overall.

The method is based on discounted cash flow analysis, which allows the calculation of the present value of cash inflows and outflows over the project's time horizon. The DCFA is applied in the preliminary phase with dual purposes: first, to verify the financial feasibility of alternative scenarios; second, to provide a basis for using the LCC approach.

The approach is based, firstly, on determining the scope/context of the analysis, including defining the time frame and system boundary. Then, the semi-analytical determination (by typological macro-items) of the cost components, both direct and indirect, is made with reference to the analyzed scenarios. Follows the estimation of expected revenues, appropriately segmented by product type, the definition of the time profile of the cash flows, distinguishing the initial investment, management, and economic return phases, and the determination of the discount rate, based on the risk associated with the project. Finally, the calculation of the leading profitability indicators, specifically Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PB), is conducted, accompanied by the interpretation of the analysis results [52].

Operationally, the DCFA is applied through spreadsheets to ensure flexibility in the analysis. The DCFA is used as an economic and financial evaluation tool to quantify the expected profitability of the investment over a defined time horizon [53].

Following the financial feasibility assessment, based on the data used for the DFCA application, the LCC approach is applied in accordance with the principles defined in the international standard ISO 15686-5:2017 [37]. The LCC approach enables the calculation of the overall cost of a production system over its entire life cycle. The operational phases to follow for applying the LCC approach are as follows [54]:

- Definition of the functional unit and analytical context: In accordance with the provisions for environmental (LCA) and social (S-LCA) impact assessments, the first step consists of defining the unitary function and defining the system boundary, which are essential for ensuring the consistency of the assessment. In this phase, all significant activities and stages of the life cycle of the analyzed system are identified, from initial implementation to operational management, considering the technical and functional specifics of the intervention under study.
- Identification of cost components: An analytical cost map is produced, distinguishing between direct costs (e.g., materials, equipment, labor, energy) and indirect costs (e.g., technical support, depreciation, related services). The identified costs are organized by activity and time frame across the life cycle under consideration, considering the "relevant" cost items.
- Definition of the time profile of flows: A time profile of costs is constructed, distinguishing between initial investment and implementation of the intervention; management/maintenance; and end-of-life.
- Modeling of alternative scenarios: Previously identified, these differ from the reference scenario due to the introduction of specific technologies (e.g., systems, materials, processes). Each scenario is described using quantitative data consistent with the reference technical specifications and includes estimates of purchase and installation costs, energy consumption, and additional labor.
- Implementation in an evaluation model: All the information collected is organized in a spreadsheet to simulate the annual economic flows associated with the life cycle. The model allows for parameterization of economic variables (unit costs, quantities, frequencies); automatic calculation development, with links between sheets to ensure internal consistency; and direct comparison between scenarios, facilitating the interpretation of results.
- Calculation of synthetic economic and financial indicators: The model calculates the leading economic sustainability indicators, specifically: Net Present Value (NPV), Payback Period (PBP), Net Savings (NS), Savings to Investment Ratio (SIR), and Adjusted Internal Rate of Revenues (AIRR) [52].

Note that the LCC model is also implemented in SimaPro to analyze the economic sustainability of the product/process system under study throughout its life cycle.

4.3. Step 3—Impact Monetization

The model proposed by Fregonara [55] introduces an integrated approach that combines the Global Cost calculation equation with some monetized environmental components to generate a synthetic economic–environmental indicator, expressed in euros (€) as the unit of measurement. The proposal is revisited here and extended to include social components, which are also monetized.

The monetization of environmental and social impacts is conducted by assigning economic values based on market prices, thereby ensuring consistency in measurement units across the different impacts. Specifically, once the unit monetary value of the impacts has been identified (derived from market sources or socioeconomic evaluation studies such as GIVE [50]), these values are multiplied by the environmental impact quantity determined using the LCA methodology. The result of this process is the expression of environmental and social impacts in economic terms, allowing their integration into the overall cost calculation and leading to a holistic sustainability assessment.

4.4. Step 4—Joint Global Cost Calculation

The fourth operational step involves calculating the joint indicator to assess overall performance. The joint indicator, as proposed in Fregonara [55], integrates the Global Cost equation [40] that monetizes environmental and social impacts. Therefore, the environmental, social, and economic Global Cost is formalized in Equation (1):

$$CG_{EnSocEc} = \Sigma C_i + \Sigma C_{En} + \Sigma C_{Soc} + \Sigma\ (C_m + C_r)/(1 + r)^t + (C_{dm} + C_{dp} - V_r)/(1 + r)^N \quad (1)$$

where $CG_{EnSocEc}$ stands for the Global Cost environmental, social and economic costs; ΣC_i stands for the sum of initial investment costs; ΣC_{En} stands for the sum of environmental costs; ΣC_{Soc} stands for the sum of social costs; C_m stands for maintenance costs; C_r stands for replacement costs; C_{dm} stands for dismantling/demolition costs; C_{dp} stands for disposal costs; V_r stands for residual value of the component at the end of the analyzed period; t stands for the cost reference year; N stands for the number of years in the time horizon selected for the analysis; and r stands for discount rate.

The quantification of the residual value (V_r), i.e., the value that an asset will have at the end of its service life, occurs according to the provisions of the EN 15459:2007 standard [40].

The equation can be adapted ad hoc to different case studies, taking into account the environmental, social, and economic specificities of the contexts analyzed.

4.5. Step 5—Results and Option Ranking

The final step, outlined in Figure 9, involves interpreting the results by analyzing the obtained output to support the selection of the most sustainable alternative or the ranking of alternatives. This step is strictly correlated with the viewpoint of the different stakeholders involved in the decision-making process. The choice of the preferred option is based on a comparison of the results from the environmental, social, and economic indicators analyzed in parallel (Step 2) as well as the integrated economic, social, and environmental indicator (Steps 3 and 4), calculated for each alternative outlined in the initial phase of the process (Step 1).

The final decision should incorporate, in addition to quantitative aspects, qualitative dimensions, regulatory constraints, and strategic considerations, to ensure a robust decision-making process consistent with sustainability principles.

Within this research project, a systematic review of the state of the art was conducted to explore the interactions among methods used to assess environmental, social, and economic sustainability.

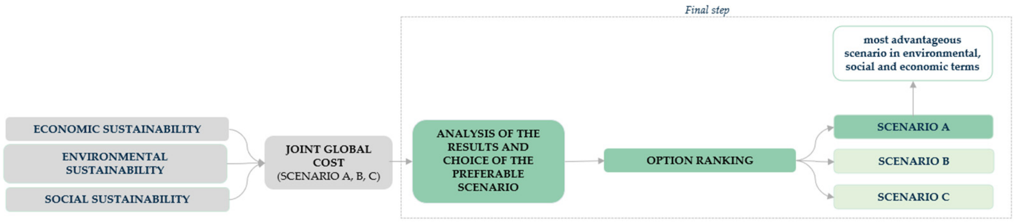

Figure 9. Graphical summary of the final phase of the evaluation methodology (source: authors' elaboration).

5. Discussion

This study, structured around a critical review of the state of the art, the definition of an integrated methodological framework, and its subsequent articulation into operational phases, highlights the need to equip decision-making processes with assessment tools capable of capturing the complexity of sustainability across its environmental, economic, and social dimensions. The analysis assumes that the joint adoption of LCA, LCC, and S-LCA within a framework grounded in Life Cycle Thinking principles represents a crucial step toward overcoming the methodological fragmentation that still characterizes much of the existing literature, which remains oriented mainly toward partial or unidimensional evaluations.

The proposed pathway is based on the operational relevance of a workflow developed to guide scenario definition, structured data collection, process modeling, and the development of comparable indicators. However, it was not possible to use the S-LCA results directly in the overall indicator. Therefore, this dimension was integrated with the GIVE model, which allows the social impacts of CO_2 to be monetized. The integration of environmental and social components within the Global Cost calculation, through monetization procedures supported by consolidated reference values, constitutes a methodological advancement over conventional approaches and enables a unified interpretation of heterogeneous phenomena expressed through different units of measurement.

Nevertheless, the study also identifies several critical issues requiring further theoretical and operational refinement. Challenges related to data availability and quality, variability in sources, the coexistence of non-homogeneous units of measurement, and the difficulty of translating social and environmental impacts into economic terms may affect the robustness and replicability of results. Many authors argue that the geographical scope can significantly alter the magnitude of results from environmental monetization methods [56]. On the other hand, several authors highlight the strategic role of monetary valuation of environmental impacts [57]. In addition, the relevance of assumptions made in scenario construction and indicator selection underscores the importance of transparency, logical consistency, and stringent uncertainty management.

Furthermore, as mentioned in Section 4.3, the complexity generated by the contextual treatment of three different sustainability dimensions is strongly linked to uncertainty and consistency issues, which can influence the ranking of options. Therefore, to ensure the robustness of the analysis, the proposed methodology must be complemented by appropriate checks of the degree of output perturbation caused by uncertainty in the input data through deterministic or probabilistic sensitivity analyses [58]. Regarding the issue of consistency between the three dimensions, further specific refinements based on the literature addressing this issue are needed.

6. Conclusions

The study contributes to the scientific debate on integrated sustainability assessment by proposing a methodological framework consistent with the European regulatory framework aimed at decarbonizing production systems, achieving climate neutrality, and transitioning to circular economy models.

Despite the limitations described in Section 5, the methodological framework outlined herein exhibits substantial potential for application in contexts characterized by innovative production processes, evolving supply chains, and strategies oriented towards material circularity. The integrated approach supports comparing alternative options, assessing impacts across the life cycle, and identifying preferences aligned with multidimensional sustainability objectives.

The main theoretical and methodological contribution consists in overcoming the fragmentation between sustainability dimensions by integrating approaches within a framework consistent with Life Cycle Thinking.

A key element of the model is the inclusion of the monetization of environmental and social impacts in the calculation of the Global Cost, which allows for the internalization of externalities normally excluded from traditional economic and financial analyses. This allows for the reconciliation of heterogeneous indicators with a single unit of measurement and the comparison of alternative scenarios using a homogeneous metric.

From an application perspective, structuring the workflow into replicable operational steps facilitates its adaptability to different production contexts and scales of analysis, serving as a tool to support strategic planning and the comparative evaluation of project alternatives. Future developments in the research include applying the model to a case study and subsequently extending it to different production contexts, assessing the sensitivity of indicators to technical and socioeconomic variables, and progressively adopting more reliable, scientifically validated datasets. These directions appear essential to consolidate robust assessment tools that support informed, transparent decisions, thereby contributing to the development of production systems that synergistically integrate environmental, economic, and social dimensions.

Author Contributions: Conceptualization, E.F. and F.T.; methodology, E.F., F.T., C.S., M.A.M.V., A.M., R.G. and D.G.F.; software, F.T. and A.M.; investigation, E.F., F.T., C.S., M.A.M.V., A.M., R.G. and D.G.F.; writing—original draft preparation, E.F., F.T., C.S., M.A.M.V. and A.M.; writing—review and editing, E.F., F.T., C.S., M.A.M.V. and A.M.; visualization, C.S., M.A.M.V. and A.M.; supervision, E.F. and F.T. All authors have read and agreed to the published version of the manuscript.

Funding: This study was conducted as part of the MICS (Made in Italy Circolare e Sostenibile) Extended Partnership, funded by the European Union—NextGeneration EU (National Recovery and Resilience Plan (NRRP)—MISSION 4 COMPONENT 2, INVESTMENT 1.3—D.D. 1551.11-10-2022, PE00000004). The views and opinions expressed are those of the authors alone and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission may be held responsible for them.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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