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An Integrated Multi-Method Framework for Assessing Sustainability of Industrial Bio-Based Systems: Approach and Application to a Textile Case Study

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Abstract

Bio-based and circular value chains require integrated sustainability assessment, yet environmental, social and economic methods are often applied in isolation. This paper presents the BIORADAR Integrated Multi-Method Sustainability Framework (BIMMSF), which links a harmonised cradle-to-gate life-cycle inventory to an indicator-based integration of Life Cycle Assessment (LCA), indirect land-use change (iLUC), Emergy evaluation, SHDB-based Social LCA (risk screening), Life Cycle Costing (LCC) and Eco-Cost. BIMMSF avoids a single composite score and instead supports cross-pillar interpretation of hotspots and trade-offs. The framework is illustrated through a proof-of-concept textile case study comparing wool, PLA, viscose, lyocell and hemp fabrics (functional unit: 1 kg). Including iLUC strongly amplifies climate relevance for land-intensive chains (e.g., wool: 52.0 kg CO_2eq kg^{-1} direct and 182 kg CO_2eq kg^{-1} iLUC), while Emergy highlights very high embodied ecological work for viscose. Social risk screening and economic indicators jointly identify wool as the most critical configuration and hemp as the best-performing option within the analysed set. The proposed framework helps reduce the risk of burden shifting by making cross-dimensional sustainability drivers explicit.

Keywords: Life Cycle Sustainability Assessment; Indicator-based assessment; Methodological integration; Sustainability trade-offs; Value chain analysis; Emergy evaluation; Social Life Cycle Assessment; Eco-Cost

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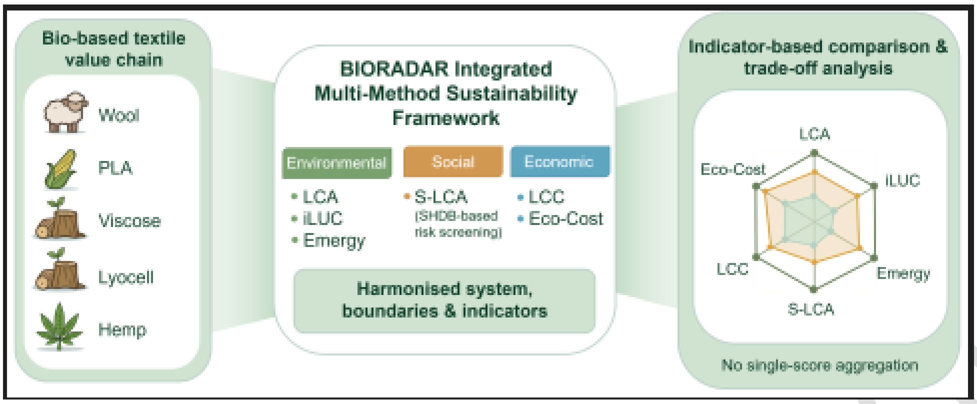
Graphical abstract



1. Introduction

Humanity is facing what is likely the greatest challenge in its history: sustaining a constantly growing population with increasing material and energy demands, while remaining within the limits of planetary boundaries (PBScience, 2025; Rockström *et al.*, 2009). Nature is inherently constrained, governed by spatial and temporal limits imposed by the immutable laws of thermodynamics (Tiezzi, 2006). Given the systemic and multifaceted nature of this challenge, a wide range of complex and interdependent solutions is required. Among these, the transition toward bio-based industrial systems plays a pivotal role, given its potential to lower fossil resource dependence, mitigate climate impacts, and stimulate the transition toward more circular and sustainable production models (EC, 2018). The European Union (EU) has made the bioeconomy a strategic pillar of the Green Deal and the Circular Economy Action Plan, encouraging the development of bio-based materials and products across multiple sectors, including textiles, packaging and agriculture. However, despite this expansion, recent research highlights that bio-based does not automatically mean more sustainable, with sustainability outcomes varying widely across products and contexts and often involving trade-offs that cannot be assumed a priori (Khanna *et al.*, 2024; Pérez-Hernández *et al.*, 2025; Zuiderveen *et al.*, 2023). The environmental and socio-economic performance of bio-based value chains is highly context-dependent, with outcomes influenced by land occupation, agricultural practices, energy inputs, chemical use and labour conditions (Ladu & Morone, 2024). The rapid growth of the bioeconomy is also accompanied by new uncertainties and potential trade-offs, such as land-use pressures, impacts on biodiversity and competition with food production (Bianchi *et al.*, 2024; Gawel *et al.*, 2019). As a result, robust sustainability assessment methods are essential to ensure that the bio-based transition delivers substantive environmental and social benefits (Wesseler & von Braun, 2017). In parallel with the expansion of the bioeconomy, increasing attention is being devoted to waste valorisation strategies aimed at converting agricultural, industrial and post-consumer residues into energy carriers and bio-based products (Demichelis *et al.*, 2025; EC, 2018; Pinheiro & Symochko, 2025). These approaches are central to circular economy policies, as they promise to reduce reliance on virgin resources while closing material loops and improving resource efficiency. However, recent studies highlight that waste valorisation does not automatically translate into sustainability gains, as environmental, economic and social trade-offs may arise depending on feedstock characteristics, processing technologies, energy inputs and supply-chain organisation (Romero-Perdomo & González-Curbelo, 2023; Wei *et al.*, 2024; Wine & Yang, 2026). In this context, robust life cycle–based sustainability assessment frameworks are essential to evaluate whether waste-derived and bio-based products effectively deliver net benefits across environmental, economic and social dimensions. Despite the increasing availability of assessment tools, sustainability evaluations of bio-based systems often rely on single-method approaches, which provide only partial insights. Life Cycle Assessment (LCA) is the most widely applied method; however, it has well-known limitations, including strong dependence on system boundaries, limited coverage of socio-economic aspects and sensitivity to data variability, which can lead to incomplete or misleading sustainability conclusions (Barahmand & Eikeland, 2022; Ranundeniya *et al.*, 2025). This limitation becomes particularly critical in the assessment of waste valorisation pathways, where reductions in fossil resource use may be accompanied by increased energy demand, land pressure or social risks along upstream and downstream supply chains (Arias *et al.*, 2025; Siddique *et al.*, 2024; Wine & Yang, 2026). Furthermore, conventional LCA often struggles to adequately represent the sustainability of natural biotic resources—such as agricultural feedstocks, forest biomass or natural fibres—because it lacks indicators for renewability, regeneration rates and ecosystem carrying capacity. This can lead to misleading conclusions when assessing bio-based products, where the dynamics of biotic resource use are central (Crenna *et al.*, 2017). Complementary approaches such as Emergy Evaluation integrate biophysical resource accounting but cannot fully address emissions, toxicity or economic implications (Santagata *et al.*, 2020). Similarly, research on textile systems indicates that conventional LCA may fail to capture the broader consumption and logistics dynamics of clothing use, thereby masking important upstream–downstream trade-offs along the value chain (Zamani *et al.*, 2017). These limitations indicate that no single tool can comprehensively capture the complex dynamics of modern bio-based systems, in which environmental, economic and social dimensions are deeply interlinked. In response to these challenges, the scientific community has increasingly advocated for integrated sustainability frameworks capable of combining multiple complementary methodologies. The Life Cycle Sustainability Assessment (LCSA) approach—conceptually defined as the integration of LCA, Life Cycle Costing (LCC) and Social LCA (S-LCA)—has gained prominence in recent years as a promising multi-pillar architecture for holistic evaluations (Bruno *et al.*, 2025). Within the bioeconomy, the relevance of combining environmental, economic and social performance metrics is well documented, particularly for sectors characterised by heterogeneous feedstocks and geographically widespread supply chains, where socio-technical dynamics and actor coordination play a decisive role (Ding *et al.*, 2024; Fernández Ocamica *et al.*, 2024; Schipfer *et al.*, 2024). Beyond LCSA, the literature increasingly highlights the potential of integrating LCA with resource-based approaches such as Emergy Evaluation, which allows the analytical scope to be broadened by accounting for nature's work embodied in products, an aspect that becomes particularly relevant in the assessment of bio-based systems (Patrizi *et al.*, 2017; Saladini *et al.*, 2016; Sporchia *et al.*, 2025). Recent research shows that integrated sustainability assessment methods can expose trade-offs that remain masked when environmental, economic, and social performance are evaluated separately, highlighting the importance of multi-method and multi-scale approaches to inform policy and industrial decision-making (Zeug *et al.*, 2022; Marcinkowski & Haręża, 2024). Despite progress in the field, significant gaps remain, particularly regarding the availability of harmonised, sector-specific and operational tools for assessing bio-based products in a comparable and decision-supportive manner. Current certification schemes and sustainability labels are often based on fragmented indicator sets and therefore inadequately reflect the multidimensional nature of bio-based systems (Ares-Sainz *et al.*, 2025; Ladu & Morone, 2024). Recent work highlights the need for transparent, indicator-based frameworks integrating environmental, economic and social metrics, specifically designed to address the complexity of bio-based value chains (Fernández Ocamica *et al.*, 2025).

The development of such frameworks depends on both methodological convergence and the availability of robust data infrastructures capable of interfacing with heterogeneous industrial processes and data sources. Against this background, the present paper introduces the BIORADAR Integrated Multi-Method Sustainability Framework (BIMMSF), a methodological architecture developed within the BIORADAR project (www.bioradar.org) to support comprehensive and harmonised sustainability assessments of industrial bio-based systems. The framework adopts a life-cycle perspective and integrates environmental, economic and social dimensions within a unified data structure and an indicator-based logic. Rather than focusing on the standalone sustainability performance of individual products, this work demonstrates how a multi-pillar framework enables holistic and consistent assessment. By integrating complementary methods, the approach reduces the risk of sustainability blind spots and reveals cross-cutting trade-offs that may remain hidden when methods are applied in isolation.

1.1. Conceptual structure of the BIORADAR Integrated Framework

From a structural perspective, the BIMMSF is grounded in the widely recognised three-pillar concept of sustainability, whereby environmental integrity, economic viability and social well-being are treated as complementary and interdependent dimensions. While this conceptualisation underpins integrated assessment paradigms such as LCSA (Purvis *et al.*, 2019), the literature has highlighted that simplified representations of the three pillars may implicitly assume substitutability among dimensions, potentially obscuring structural dependencies and trade-offs (Pulselli *et al.*, 2015). In response to these limitations, BIMMSF adopts an integrated three-pillar structure in which environmental, economic and social assessments are developed in parallel using harmonised system boundaries, functional units and life-cycle inventories. This design ensures methodological consistency across dimensions and enables meaningful cross-pillar interpretation. As illustrated in **Figure 1**, the environmental pillar combines LCA, indirect Land Use Change (iLUC) modelling and Emergy Evaluation to capture both impact-based indicators and biophysical resource support. The economic pillar integrates simplified LCC with Eco-Cost assessment, complementing conventional cost analysis with the monetisation of environmental externalities. The social pillar is addressed through S-LCA, relying on database-based risk screening to identify potential social hotspots associated with country- and sector-specific supply chain configurations. In line with recent methodological contributions advocating indicator-based and multi-method sustainability frameworks, BIMMSF does not aggregate results into a single composite score. Instead, it preserves the analytical value of each sustainability dimension while supporting the identification of trade-offs, synergies and potential sustainability blind spots that may remain hidden when methods are applied in isolation. The resulting framework is modular and scalable, providing a literature-consistent yet operational architecture for the assessment, monitoring and benchmarking of sustainability performance in industrial bio-based systems.

Compared with existing LCSA and broader multi-criteria sustainability assessment approaches, the novelty of BIMMSF lies in four main elements: (i) the use of a harmonised life-cycle inventory, common system boundaries and functional unit across environmental, economic and social assessments; (ii) the extension of standard LCSA through the integration of iLUC, Emergy and Eco-Cost alongside LCA, SHDB-based S-LCA and simplified LCC; (iii) an indicator-based integration logic that preserves the interpretability of each method without collapsing results into a single composite score; and (iv) a proof-of-concept application showing how a unified data structure makes cross-pillar trade-offs and hotspots more explicit in bio-based textile value chains.

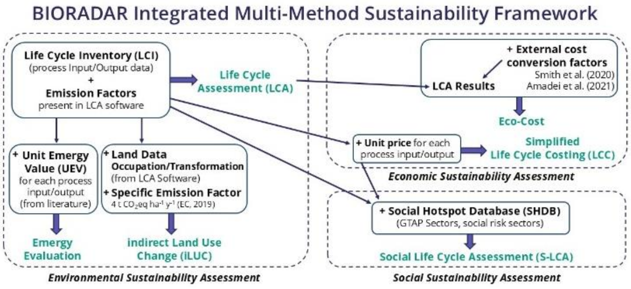


Figure 1. Schematic representation of the BIMMSF. The framework supports a multi-dimensional comparison of alternative products by jointly considering environmental, economic, and social performance indicators.

1.2. *Proof-of-concept application and paper structure*

The operational applicability of the framework is illustrated through a proof-of-concept application to five textile products—wool, polylactic acid (PLA), viscose, lyocell and hemp—selected within the BIORADAR project based on data availability and their representativeness of bio-based textile value chains with contrasting sustainability profiles. The selected materials are not intended to provide an exhaustive comparison of textile products, but rather to act as archetypal bio-based value chains characterised by different structural features, including land-intensive agricultural systems (e.g., wool), industrial and capital-intensive bio-based processes (e.g., PLA and regenerated cellulose fibres), and fibres with higher circularity and recyclability potential (e.g., hemp). This selection enables the framework to be tested across contrasting sustainability drivers, highlighting its ability to capture trade-offs that are relevant to a wide range of bio-based or waste valorisation pathways. Although the proof-of-concept application focuses on textile products, the methodological architecture of the BIORADAR framework is inherently feedstock-agnostic and can be directly applied to bio-based products derived from agricultural residues, industrial by-products and post-consumer waste streams, as commonly encountered in waste valorisation and circular bioeconomy systems. By presenting the framework's methodological structure, data requirements and integration logic, this paper contributes to the ongoing scientific discussion on how to operationalise multi-dimensional sustainability assessment in the bioeconomy. The proposed framework is modular, transparent and adaptable across sectors, providing researchers, industry stakeholders and policymakers with an operational framework for comparative sustainability screening and for supporting sustainability-oriented decision-making in the development of bio-based products and value chains.

The specific methods composing each sustainability pillar are summarised in Section 2.2 and detailed in Sections 2.1–2.4. The remainder of the paper is structured as follows. **Section 2** presents the materials and methods, including the environmental, economic and social assessment approaches, and the data harmonisation and indicator integration strategy. **Section 3** presents the results of the proof-of-concept application to the textile case study, providing integrated environmental, economic and social insights. **Section 4** discusses the implications of the results, highlighting the added value of the multi-method framework, methodological limitations and future development opportunities. Finally, **Section 5** summarises the main conclusions and outlines perspectives for further research and application.

2. Materials and Methods

2.1. *Environmental Assessment Methods*

The environmental pillar was assessed using harmonised life-cycle inventories and a cradle-to-gate scope consistent with the overall framework. Methods were selected to capture both conventional impact pathways (emissions and resource use) and bio-based specific drivers such as land-related effects and biophysical resource support. The following subsections describe the applied environmental methods and their implementation.

2.1.1. *Life Cycle Assessment*

The LCA is a standardised methodology for quantifying the potential environmental impacts associated with a product or system across its life cycle, which can cover from raw material extraction to end-of-life, in accordance with ISO 14040 and ISO 14044 standards (ISO, 2020a; 2020b). The LCA is widely used to identify environmental hotspots, trade-offs and improvement opportunities in industrial systems and represents the reference method for environmental impact assessment within life cycle–based sustainability frameworks (Guinée *et al.*, 2011; Hauschild *et al.*, 2018). Within the BIORADAR Integrated Framework, LCA constitutes the core environmental assessment method and provides the Life Cycle Inventory (LCI) backbone for integration with complementary approaches, including iLUC modelling and Emergy Evaluation. An attributional LCA approach was applied, adopting a cradle-to-gate system boundary to ensure consistency across bio-based value chains and comparability between assessed products. Environmental impacts were calculated using the Sphera LCA for Experts software (v10.7.1.28) and the Environmental Footprint (EF) methodology (v3.1) of the European Commission (EU, 2021), enabling harmonised characterisation across multiple impact categories. For the textile case study, the functional unit was defined as 1 kg of fabric, in line with common practice in textile LCA studies (Zamani *et al.*, 2017). The LCI combined: (i) foreground primary data directly collected from industrial partners and project activities for selected textile processing steps; (ii) secondary data from scientific literature and established databases (Ecoinvent v3.9.1) for background processes and missing inputs; and (iii) project-specific datasets harmonised within the BIORADAR framework. The inventories of the five textile products within the present study are shown in the Supplementary Material. Some industrial data are confidential and cannot be disclosed in raw form. Supporting inventories, source mapping, and data-quality information are documented in BIORADAR public deliverables, while the data supporting the findings of this study are available from the authors upon reasonable request.

The foreground inventories were constructed process-by-process for each textile pathway and normalised to the functional unit of 1 kg of fabric. Each inventory includes the direct material, auxiliary, electricity, transport and waste-treatment inputs required at each processing stage. No additional allocation was applied in the foreground modelling, as the analysed product systems were represented as single-product cradle-to-gate systems and no multifunctional foreground unit processes requiring co-product partition were modelled. Intermediate materials such as sheep fleece and polylactide were treated as input flows to the textile system. For secondary/background data, the modelling conventions and any embedded multifunctionality followed the default assumptions of Ecoinvent v3.9.1. **Table 1** summarises the environmental impact categories considered in the LCA, together with the corresponding units of measurement, as defined by the EF method.

Table 1. Environmental impact categories and corresponding units of measurement considered in the LCA, in accordance with the EF method.

Impact Category	Unit
Acidification	Mol of H+ eq
Climate Change	kg CO_2eq
Ecotoxicity, freshwater	CTUe
Eutrophication, freshwater	kg P eq
Eutrophication, marine	kg N eq
Eutrophication, terrestrial	Mol of N eq
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionising radiation	kBq U235 eq
Land Use	Pt
Ozone depletion	kg CFC-11 eq
Particulate matter	Disease incidences
Photochemical ozone formation	kg NMVOC eq
Resource use, fossil	MJ
Resource use, mineral and metals	kg Sb eq
Water use	m^3 world eq

2.1.2. Indirect Land Use Change

The iLUC assessment applied in this study follows the deterministic methodology developed by the European Commission (EC, 2019), which provides a generic emission factor for iLUC applicable across bio-based value chains. The EC method is grounded on historical deforestation and agricultural intensification trends from 2000–2010 and represents one of the most comprehensive and transparent approaches to quantify land-use-related greenhouse gas emissions for bio-based products. The method builds on a six-step procedure. First, the contribution of agricultural expansion versus intensification to the global iLUC response is quantified, using historical Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data on crop yields, production and cropland area. Based on these trends, the EC assigns 85% of the response to land expansion and 15% to intensification processes such as increased fertiliser use. Second, geo-spatial patterns of arable land expansion are reconstructed by combining Food and Agriculture Organization (FAO) deforestation statistics with Intergovernmental Panel on Climate Change (IPCC) biome classifications, resulting in an 82-cell region × biome matrix that tracks where agricultural expansion occurred globally. Third, the EC attributes 34% of observed deforestation to demand for arable land, following Directorate-General (DG) Environment analyses. Steps 4–5 calculate emissions from land expansion (including carbon losses from above-ground biomass, foregone sequestration over 20 years, and peatland clearing) and from intensification (mainly N, P, and K fertiliser-related emissions). Finally, the emissions from expansion and intensification are aggregated according to their respective shares to derive the generic iLUC factor, expressed in kg CO_2eq per hectare per year (4.0 t CO_2eq ha^{-1} yr^{-1}). For the BIORADAR products, this generic factor was applied by multiplying it with the total land occupation and transformation associated with each product system, derived from LCA inventory data (m^2a and m^2 converted to hectares). This procedure ensures a consistent and transparent estimation of the iLUC impact across diverse bio-based products. It should be noted that this EC-based iLUC approach is deterministic and relies on a generic emission factor derived from historical global trends rather than product-specific market responses or site-specific land-use dynamics. As such, it is suitable for comparative screening and for making land-related climate relevance visible within integrated sustainability assessment, but it cannot capture regional heterogeneity, temporal dynamics, indirect market feedbacks or future land-use trajectories. The resulting iLUC estimates should therefore be interpreted as indicative order-of-magnitude values rather than as precise predictions of actual indirect land-use change attributable to a given product system.

2.1.3. Emergy Evaluation

"Plants are the link that connects the Sun to the Earth," as stated by the Russian botanist Kliment Timirjazev (Mancuso, 2023), underscoring the role of solar energy in biospheric processes. In this biophysical context, Emergy evaluation, originally developed by Odum (1971) is a thermodynamics-based environmental accounting approach that quantifies the environmental support required to generate a product or service. Grounded in open-systems thermodynamics, Emergy quantifies the biophysical support embodied in a product or process; because it is path-dependent (i.e., not a state function), results depend on the specific production route (Saladini *et al.*, 2016). By accounting for the total contribution of environmental inputs, Emergy helps characterise the relationship between human-dominated systems and the biosphere (Pulselli *et al.*, 2014). Emergy is defined as the amount of available energy (exergy) of one kind - commonly expressed as solar Emergy - that is directly and indirectly required to produce a service or product (Bastianoni *et al.*, 2007; Odum, 1971; 1988; 1996). All energy, material and service inputs are converted into a common unit, the solar equivalent Joule (sej), using Unit Emergy Values (UEVs) as conversion factors (Odum, 1996; De Vilbiss *et al.*, 2024). In practice, the assessment starts with the definition of system boundaries, a reference unit (similar to the concept of the FU in LCA) and the construction of an Emergy diagram to identify relevant inflows and outflows. Each input is multiplied by its corresponding UEV and independent inputs are summed to obtain the total Emergy supporting the system (Odum, 1996). To ensure comparability across studies, Emergy accounting adopts the Geobiosphere Emergy Baseline (GEB), currently set at 1.20 E+25 seJ yr^{-1} (Brown & Ulgiati, 2016). Among Emergy-based indicators, the UEV (or transformity) expresses the Emergy required per unit of output, while the Renewability Rate (%R) quantifies the share of total Emergy derived from renewable sources (e.g., sunlight, rainfall, wind and geothermal heat) relative to non-renewable or imported inputs (Odum *et al.*, 2000; Patrizi *et al.*, 2018). Together, these indicators support the interpretation of resource-use patterns beyond conventional impact metrics. In this study, UEVs and transformities were selected from peer-reviewed literature and harmonised to ensure consistency with the foreground inventory. The complete set of UEVs adopted for the analysed textile products is reported in **Table 2**.

Table 2. UEVs and transformities used in this study for the Emergy assessment of the analysed textile products. All UEV and transformity values are referenced to the GEB of 1.20E+25 seJ yr^{-1} (Brown & Ulgiati, 2016); MSW denotes municipal solid waste.

Item	Value	sej/unit	Reference	%R
Solar radiation	1	sej/J	Odum, 1996	100%
Rain	1.09E+05	sej/g	Odum *et al.*, 2000	100%
Wind	1.24E+03	sej/J	Campbell & Erban, 2017	100%
Geothermal heat	7.78E+03	sej/J	Odum *et al.*, 2000	100%
Water - Aqueduct	2.39E+06	sej/g	Pulselli *et al.*, 2011	29%
Transport	6.97E+04	sej/gkm	Pulselli *et al.*, 2008	0%
Waste Incineration	4.88E+08	sej/g MSW	Marchettini *et al.*, 2007	0%
Electric Energy	2.21E+05	sej/J	Bastianoni *et al.*, 2009	0%
Coal	6.03E+09	sej/g	Campbell, Lu, Walker, 2014	0%
Rubber	3.51E+09	sej/g	Pulselli, 2010	0%
Wool/Sheep	9.00E+08	sej/g	dos Reis *et al.*, 2021	34.2%
Paper and cardboard	2.65E+09	sej/g	Pulselli, 2010	0%
Seeds	2.26E+09	sej/g	Fahd *et al.*, 2012	0%
PET (Polyethylene Terephthalate)	4.50E+09	sej/g	Bustamante *et al.*, 2016	0%
Chemicals - generic	4.84E+08	sej/g	Odum, 1996	0%
Glycerin *(Glycerol)*	9.17E+10	sej/g	Fahd *et al.*, 2012	0%
Lactic Acid	2.13E+11	sej/g	Flora, 2022	4.1%
Ethylene	4.85E+09	sej/g	Bustamante *et al.*, 2016	0%
Sodium hydroxide	3.19E+09	sej/g	Giannetti *et al.*, 2015	0%
Hydrochloric acid	1.41E+10	sej/g	Giannetti *et al.*, 2015	0%
Sulfuric acid	6.54E+09	sej/g	Giannetti *et al.*, 2015	0%
Hydrogen sulfide	1.21E+09	sej/g	Giannetti *et al.*, 2015	0%
Manganese (II) sulfate	2.53E+11	sej/g	Giannetti *et al.*, 2015	0%
Ammonium nitrate	4.83E+09	sej/g	Baral & Bakshi, 2010	0%
Superphosphate	5.85E+09	sej/g	Baral & Bakshi, 2010	0%
Silicon	1.70E+09	sej/g	Campbell, Lu, Walker, 2014	0%

2.2. Social Assessment Method

2.2.1. Social Hotspot Database (SHDB)-based risk screening

Given the complexity and geographical dispersion of textile value chains, as well as the limited availability of reliable site-specific social data, the social assessment was conducted using a risk-based S-LCA approach. A product-level social risk assessment was therefore performed using the Social Hotspot Database v5 (Bennema *et al.*, 2022; SHDB, 2025), implemented within the SimaPro software v10.2 (SHDB, 2025). The SHDB provides country- and sector-specific social risk indicators covering a wide range of social topics, including labour rights and decent work, health and safety, governance, and community infrastructure. The SHDB-based assessment follows a risk-screening logic, whereby LCI flows are linked to economic sectors and geographic regions through a GTAP-derived multi-regional input–output model (Bennema *et al.*, 2022; SHDB, 2025). Each country–sector combination is associated with qualitative risk levels (i.e., low, medium, high, very high) for more than 200 social indicators, enabling the identification of potential social hotspots embedded in upstream supply chains. These indicators represent elementary risk metrics covering a wide range of social themes and are systematically aggregated within the SHDB framework into broader impact categories and sub-categories. In the present study, all underlying SHDB indicators were considered through this aggregation structure, while results are reported at the category and sub-category level to support interpretability and comparability. Consistency across tools was ensured by using the same cradle-to-gate LCI (FU: 1 kg fabric) developed for the LCA as the common backbone. The inventory flows were exported and mapped to SHDB v5 country–sector combinations in SimaPro v10.2 while keeping identical system boundaries and excluding any processes outside the LCA scope (see **Table 3**). In the SHDB implementation, inventory inputs were modelled as country-specific purchases expressed in USD 2011; accordingly, inputs were assigned to Italy (/ITA/U) for the textile supply chains, while sheep fleece was assigned to Australia (/AUS/U), assuming Australian origin for wool production. The SHDB results were interpreted as indicative of systemic social risks rather than site-specific performance and were therefore used to prioritise areas requiring further investigation or stakeholder engagement. Accordingly, the SHDB-based results should not be interpreted as measured or realised social impacts at company or site level. They represent a screening-based estimate of potential social risk exposure embedded in the assessed supply chains, derived from country- and sector-level risk profiles. Social risk results are expressed in medium risk hours equivalents (mrheq), an intensity-based unit that represents the potential exposure of workers to medium-level social risks per functional unit. The mrheq indicator combines information on the magnitude of economic activity, sector- and country-specific risk levels, and labour intensity, and is commonly used in SHDB-based S-LCA studies to enable comparative interpretation of social risk profiles across products and supply chains. Higher mrheq values indicate a greater potential exposure to social risks embedded in the assessed value chain. For result interpretation and clarity, social assessment outcomes are presented in Section 3 in aggregated form at the category level (**Table 5**, showing results for the five categories, namely Labour Rights & Decent Work, Health & Safety, Society, Governance, and Community), and with subcategory details (**Table 6**).

Table 3. Mapping of the main inventory inputs to GTAP v9 sector codes used in the SHDB v5 country–sector linking (SimaPro v10.2).

Process Input	**GTAP 9 Sectoral List**		
	N.	**Code**	**Description**
Auxiliaries (textile auxiliaries); Carbon disulfide (CS_2); Cleaning products; Cross-linking agent; Generic chemical (unspecified); Glycerol (glycerine); Hydrochloric acid (HCl); N-methylmorpholine N-oxide (NMMO); Polylactide (PLA); Polypropylene; Silicone; Sodium hydroxide (NaOH); Sulfonate (generic); Sulfuric acid (H_2SO_4); Zinc sulfate ($ZnSO_4$)	33	CRP	Chemical, rubber, plastic products
Water/Softened water	53	WTR	Water
Sheep fleece	12	WOL	Wool, silk-worm cocoons
Seed (hemp)	7	PFB	Plant-based fibres
Pulp	30	LUM	Wood products
Coal	15	COA	Coal
Oil for spinning, Diesel for machinery, lubricant	32	P_C	Petroleum, coal products
Natural gas	17	GAS	Gas
Electricity	43	ELY	Electricity
Transport	48	OTP	Transport

2.3. Economic Assessment Methods

The economic pillar was used to interpret sustainability results in terms of production costs and external environmental burdens. A streamlined approach was adopted to ensure consistency with available inventory data and the multi-actor nature of textile value chains. The following subsections describe the costing and monetisation approaches applied.

2.3.1. Life Cycle Costing

The LCC analysis was conducted to estimate and compare the production costs of selected bio-based fabrics within the framework of LCSA. In line with the BIORADAR methodological approach, a process-based simplified LCC was applied to the textile sector reflecting the high complexity, fragmentation, and limited data availability characterising textile value chains (De Menna *et al.*, 2018; Swarr *et al.*, 2011). The applied LCC focuses on production-related costs and does not include capital expenditures (CAPEX), facility lifetime modelling, or discounting of cash flows. This choice was motivated by the multi-actor nature of textile supply chains, where successive transformation steps (e.g., fibre production, spinning, weaving, finishing) are typically performed in separate facilities, making the allocation of capital costs and investment horizons highly uncertain and context-dependent (De Menna *et al.*, 2018). The system boundaries and FU of the textile LCC assessment correspond to those adopted in the environmental LCA. The LCC calculation was based on the life cycle inventory developed for the LCA, assigning unit economic values to each input/output flow. Unit prices were collected from market databases, scientific literature, and industrial sources, primarily including: (i) official EU statistics and indicators (ecb.europa.eu; ec.europa.eu; agridata.ec.europa.eu); (ii) commodity and energy price portals (tradingeconomics.com; globalpetrolprices.com); (iii) sector-specific market intelligence and costing databases (procurementresource.com; chemanalyst.com; statista.com; intratec.us); and (iv) supplier catalogues for chemicals and auxiliaries (sigmaaldrich.com), complemented by peer-reviewed literature and industrial quotations. Unit prices were subsequently harmonised to a common reference year (2025) through currency conversion and inflation adjustment using official European Central Bank (ECB) indicators. Unless otherwise specified, prices refer to EU market conditions, were converted to EUR where needed (ECB exchange rates), and adjusted to 2025 using ECB inflation indicators. Costs were modelled as operating production costs (OPEX) only, consistently with the inventory-based approach, and therefore exclude CAPEX and discounting. The total production cost per FU was obtained by multiplying the quantity of each inventory input by its corresponding unit price and summing all cost contributions. The resulting LCC values represent indicative production costs, suitable for comparative analysis and hotspot identification, rather than a full economic appraisal. Because capital expenditures are excluded, these values may underrepresent the total economic burden of production pathways characterised by high capital intensity, long asset lifetimes or infrastructure-dependent processing. They should therefore be interpreted as indicative operating production costs for comparative screening, rather than as full techno-economic or investment appraisals. Environmental externalities were not monetised within the LCC and were instead addressed separately through the Eco-Cost assessment.

Table 4. Eco-Cost monetisation factors (€/unit of impact) for the considered environmental impact categories, based on Smith *et al.* (2020) and Amadei *et al.* (2021). When available, values were averaged across the two sources.

Impact Category	Smith et al. (2020) EUR2018/unit	Amadei et al. (2021) EUR2019/unit	Average EUR/unit
Acidification	0.39 €	0.38 €	0.38 €
Climate Change	0.12 €	0.07 €	0.09 €
Ecotoxicity, freshwater	0.00004 €	0.00004 €	0.00004 €
Eutrophication, freshwater	2.16 €	2.14 €	2.15 €
Eutrophication, marine	3.61 €	7.26 €	5.44 €
Eutrophication, terrestrial	-	-	-
Human toxicity, cancer	1,020,000 €	887,000 €	953,500 €
Human toxicity, non-cancer	184,000 €	174,000 €	179,000 €
Ionising radiation, human health	0.001 €	0.23 €	0.12€
Land Use	0.002 €	0.0002 €	0.001€
Ozone depletion	35.30 €	60.60 €	47.95 €
Particulate matter	883,000 €	872,000 €	877,500 €
Photochemical ozone formation, human health	1.34 €	3.84 €	2.59 €
Resource use, fossils	0.001 €	0.01 €	0.01 €
Resource use, mineral and metals	1.85 €	1.81 €	1.83 €
Water use	0.01 €	0.01 €	0.01 €

2.3.2. Eco-Cost assessment

To complement the environmental and economic evaluation of the selected bio-based systems, an Eco-Cost analysis was performed to monetise the environmental impacts associated with each system over its life cycle. The Eco-Cost methodology converts midpoint life cycle impact indicators - such as kg CO_2-equivalents, mol H^+-equivalents or comparative toxic units (CTUh) - into a single monetary metric expressed in euros per functional unit. This approach enables the aggregation of heterogeneous environmental impacts into a unified economic indicator, supporting the identification of trade-offs between environmental damage and economic performance. The Eco-Cost concept represents the hidden environmental costs borne by society because of pollution and resource depletion, even when such costs are not reflected in market prices. It can be interpreted as the cost required to prevent, mitigate or remediate environmental damage and is therefore considered a proxy for the shadow price of environmental impacts (Amadei & Sala, 2025; de Bruyn *et al.*, 2018). This interpretation is consistent with established approaches in the literature. Amadei *et al.* (2021) provide a comprehensive review of monetary valuation methods in LCA, describing the theoretical basis for deriving monetary valuation coefficients from damage cost, abatement cost and willingness-to-pay approaches. In parallel, Smith *et al.* (2020), in a report for the European Commission, propose a harmonised and Product Environmental Footprint (PEF)-compatible set of monetisation factors designed to support policy-relevant environmental cost assessments at the EU level. In this study, midpoint LCA results were multiplied by category-specific monetisation factors expressed in €/unit of impact. Where values from both sources were available, the average of the two coefficients was applied (see **Table 4**). The monetised impacts were subsequently summed across all impact categories to obtain a total Eco-Cost per functional unit. Eco-Cost values were not adjusted to a common reference year (e.g., 2025), as the Eco-Cost assessment remains independent from the LCC analysis. Since the conversion factors were derived as averaged literature values, further inflation adjustments were considered unnecessary. Negative midpoint impact results were set to zero, as they do not represent environmental damage and therefore do not imply prevention or remediation costs.

Table 5. Environmental, social and economic results for the five textile fabrics assessed with the BIORADAR BIMMSF (FU: 1 kg of fabric). The table combines LCA, iLUC, Emergy, S-LCA, LCC and Eco-Cost indicators derived from harmonised life cycle inventories, enabling cross-dimensional comparison of sustainability performance and trade-offs. The largest value is highlighted in bold. For readability, values in the range 10^{-2}–10^{2} are reported in decimal form, while values outside this range are reported in scientific notation.

Method.	**Impact Category**	**Unit**	**Results**				
			Wool	**PLA**	**Viscose**	**Lyocell**	**Hemp**
LCA	Acidification	Mol of H+ eq	1.10	0.02	7.77E-03	7.93E-03	3.80E-03
	Climate Change	kg CO_2eq	52	7.43	2.96	2.81	2.64
	Ecotoxicity, freshwater	CTUe	1.18E+03	97.20	0.03	0.01	19.20
	Eutrophication, freshwater	kg P eq	0.01	3.82E-05	1.56E-03	6.58E-04	1.31E-04
	Eutrophication, marine	kg N eq	0.18	5.56E-03	0.01	6.50E-03	2.30E-03
	Eutrophication, terrestrial	Mol of N eq	4.88	0.06	0.02	0.02	0.02
	Human toxicity, cancer	CTUh	1.20E-08	7.75E-09	2.51E-08	9.64E-09	1.10E-09
	Human toxicity, non-cancer	CTUh	7.75E-07	1.69E-07	1.41E-06	5.57E-07	1.11E-07
	Ionising radiation	kBq U235 eq	0.36	0.64	0.26	0.24	0.17
	Land Use	Pt	5.05E+03	133	18.20	171	89.30
	Ozone depletion	kg CFC-11 eq	1.11E-07	7.09E-10	1.02E-08	2.70E-08	1.52E-11
	Particulate matter	Disease incidences	7.80E-06	1.37E-07	8.20E-08	1.27E-07	3.53E-08
	Photochemical ozone formation	kg NMVOC eq	0.05	0.01	5.60E-03	6.94E-03	3.24E-03
	Resource use, fossil	MJ	97.80	10.7	5.89	4.07	2.27
	Resource use, mineral and metals	kg Sb eq	7.57E-05	6.74E-06	2.47E-05	9.04E-06	1.71E-06
	Water use	m^3 world eq	34.80	3.07	0.64	-0.33	0.11
Emergy	Unit Emergy Value	sej g^{-1}	6.25E+09	2.58E+10	7.19E+11	2.58E+10	3.43E+09
	Renewability Rate	%R	5.56%	3.97%	0.00%	0.03%	7.16%
iLUC	/	kg CO_2eq	182	2.00	1.94	1.94	1.58
S-LCA	1. Labor Rights & Decent Work	Mrheq	1.59	0.76	0.84	0.66	0.39
	2. Health & Safety	Mrheq	0.43	0.22	0.24	0.19	0.12
	3. Society	Mrheq	0.75	0.38	0.41	0.32	0.19
	4. Governance	Mrheq	0.50	0.24	0.26	0.20	0.13
	5. Community	Mrheq	0.65	0.33	0.36	0.28	0.17
LCC	/	€	9.30	5.35	4.87	4.22	1.42
Eco-Cost	/	€	19.80	1.88	1.18	1.03	0.81

***Note**: Negative values for the Water Use impact category may occur due to the application of the EF water scarcity method, which accounts for regional water scarcity and potential credits associated with upstream processes. In the case of lyocell, the negative result reflects modelling assumptions related to background data and water use characterisation factors and should not be interpreted as a net water generation, but rather as a relative outcome of the LCI and impact assessment method.*

2.4. Indicator normalisation and visual integration

To support the integrated visual comparison of environmental, social and economic results, the selected indicators were normalised using a min-max approach (0 = best relative performance; 1 = worst relative performance) and visualised through a multi-pillar radar chart. Normalisation was performed across the range of values observed within the analysed case study, ensuring internal consistency among the selected products. This procedure was applied exclusively for visual integration and comparative interpretation purposes and does not imply aggregation into a composite sustainability score. The visual integration does not imply metric commensurability among indicators. In particular, Emergy indicators are used as complementary diagnostic information on biophysical resource support and renewability, rather than as values directly comparable to LCA midpoint impacts.

2.4.1. The Case Study: Textile Products

The full set of environmental, social and economic results for the five fabrics (wool, PLA, viscose, lyocell and hemp) is reported in **Table 5**, illustrating the integrated outputs of the proof-of-concept application of the BIORADAR framework, rather than aiming to identify a single "most sustainable" material.

To provide a more transparent and informative interpretation of the social assessment results, an additional table reporting the underlying S-LCA sub-categories is presented. This detailed breakdown complements the aggregated results shown in **Table 6**, clarifying the specific social risk dimensions captured by broad categories such as "Society" and "Governance", which would otherwise remain difficult to interpret in operational terms.

Table 1. *Social risk results by SHDB sub-category (mrheq per FU) for wool, PLA, viscose, lyocell and hemp. The table complements the aggregated social categories in* ***Table 5*** *and allows a more detailed interpretation of social risk drivers.*

Categories & Subcategories	Unit	Wool	PLA	Viscose	Lyocell	Hemp
1. Labor Rights & Decent Work	mrheq	1.59	0.76	0.84	0.65	0.39
1A Wage assessment	mrheq	0.20	0.09	0.10	0.08	0.04
1C Workers in poverty	mrheq	0.14	0.07	0.08	0.06	0.04
1D Child Labor	mrheq	0.12	0.07	0.07	0.06	0.03
1E Forced Labor	mrheq	0.20	0.10	0.11	0.09	0.05
1F Excessive Worktime	mrheq	0.19	0.09	0.10	0.07	0.05
1G Freedom of Association	mrheq	0.18	0.07	0.08	0.06	0.04
1H Migrant Labor	mrheq	0.16	0.06	0.07	0.05	0.04
1I Social Benefits	mrheq	0.07	0.03	0.04	0.03	0.01
1J Labor Laws/Conventions	mrheq	0.04	0.02	0.02	0.02	0.01
1K Discrimination	mrheq	0.16	0.09	0.10	0.07	0.04
1L Unemployment	mrheq	0.14	0.07	0.07	0.06	0.04
2. Health & Safety	mrheq	0.43	0.22	0.24	0.19	0.12
2A Occupational Toxics & Hazards	mrheq	0.21	0.10	0.10	0.08	0.05
2B Injuries & Fatalities	mrheq	0.22	0.13	0.14	0.11	0.06
3. Society	mrheq	0.75	0.37	0.41	0.32	0.19
3A Indigenous Rights	mrheq	0.06	0.03	0.04	0.03	0.01
3B Gender Equity	mrheq	0.09	0.05	0.06	0.04	0.03
3C High Conflict Zones	mrheq	0.14	0.07	0.07	0.06	0.03
3D Non-Communicable Diseases	mrheq	0.02	0.01	0.01	0.01	0.01
3E Communicable Diseases	mrheq	0.08	0.04	0.05	0.04	0.02
3F Poverty & Inequality	mrheq	0.17	0.08	0.09	0.07	0.04
3G State of Environmental Sustainability	mrheq	0.18	0.09	0.10	0.07	0.05
4. Governance	mrheq	0.50	0.24	0.26	0.20	0.13
4A Legal System	mrheq	0.18	0.09	0.09	0.07	0.05
4B Corruption	mrheq	0.08	0.04	0.05	0.04	0.02
4C Democracy & Freedom of Speech	mrheq	0.23	0.11	0.12	0.09	0.06
5. Community	mrheq	0.65	0.33	0.36	0.28	0.17
5A Access to Drinking Water	mrheq	0.05	0.04	0.04	0.03	0.02
5B Access to Sanitation	mrheq	0.13	0.06	0.07	0.05	0.04
5C Children out of School	mrheq	0.11	0.06	0.06	0.05	0.03
5D Access to Hospital Beds	mrheq	0.10	0.06	0.06	0.05	0.03
5E Smallholder vs Commercial Farms	mrheq	0.06	0.02	0.03	0.02	0.01
5F Access to Electricity	mrheq	0.05	0.03	0.03	0.02	0.01
5G Property Rights	mrheq	0.14	0.07	0.07	0.05	0.04

Figure 2 presents the integrated radar chart resulting from the normalised indicators described in Section 2.4. For the Emergy pillar, the renewable fraction (%R) was selected to highlight differences in renewable environmental support across the analysed value chains, complementing conventional life cycle–based impact indicators. For visualisation purposes, S-LCA results were aggregated by summing the five social impact categories, which share the same unit (mrheq). This aggregated indicator provides an overall representation of potential social risk exposure and does not replace the detailed category-level analysis reported in **Tables 5 and 6**. Owing to the relative

normalisation approach adopted, hemp attains normalised values equal to zero across all selected indicators in the case study range; therefore, its radar profile collapses to the centre and is represented by a red triangular marker. The radar chart is intended to illustrate cross-dimensional trade-offs enabled by the integrated framework rather than to provide definitive sustainability rankings of materials.

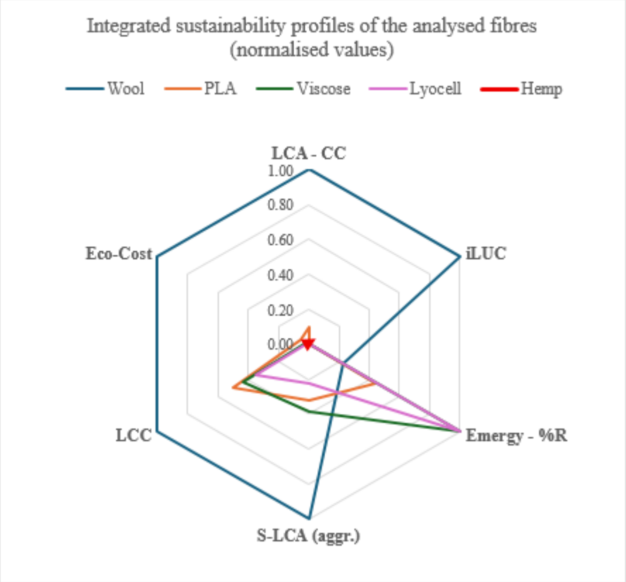


Figure 2. Integrated sustainability profiles of the analysed fabrics obtained through the BIORADAR framework. Selected environmental, social and economic indicators were normalised using a min–max approach (0 = best relative performance; 1 = worst relative performance) to support visual comparison across dimensions. Since hemp attains normalised values equal to 0 across all selected indicators, its radar polygon collapses to the centre and is represented by the red triangular marker.

2.4.2. Environmental performance (LCA, iLUC and Emergy)

The environmental assessment highlighted substantial differences in the sustainability profiles of the five analysed textile fabrics. From a **LCA** perspective, wool exhibited the highest environmental impacts across most categories. Climate change impacts amounted to 52.0 kg CO_2eq per kg of wool, compared to 7.43 kg CO_2eq for PLA and approximately 2.6-3.0 kg CO_2eq for viscose, lyocell and hemp. Similarly, wool dominated acidification, eutrophication and particulate matter formation, reflecting the high emission intensity of livestock production and feed cultivation. Land use was particularly critical, with wool reaching 5050 Pt, more than one order of magnitude higher than any other fabric. Among the man-made fibres, viscose and lyocell showed relatively low climate change impacts (2.96 and 2.81 kg CO_2eq, respectively) compared to the other fabrics but differed in other categories, notably ecotoxicity and human toxicity, which were higher for viscose due to its chemical-intensive pulping and regeneration processes. The PLA exhibited higher fossil resource use (107 MJ) than all other fabrics, reflecting the energy demand of polymerisation and auxiliary inputs, despite its biogenic feedstock origin. Hemp consistently showed the lowest or near-lowest impacts across most categories, including climate change (2.64 kg CO_2eq), particulate matter and fossil resource use (22.7 MJ).

The inclusion of **iLUC** strongly amplified the climate relevance of land-based fabrics. Wool showed an iLUC-related climate impact of 182 kg CO_2eq per kg, far exceeding its direct climate footprint and dwarfing all other fabrics. Both PLA, viscose, lyocell and hemp showed much lower and similar iLUC contributions (approximately 1.6-2.0 kg CO_2eq), reflecting their substantially lower land occupation per functional unit.

Emergy evaluation revealed further contrasts in biophysical resource support. Viscose exhibited by far the highest UEV (7.19E+11 sej g^{-1}), indicating a very high environmental work embodied in the production of regenerated cellulose fabrics. Hemp had the lowest UEV (3.43E+9 sej g^{-1}) and the highest renewability rate (7.16%), while wool showed intermediate renewability (5.56%), but very high absolute Emergy demand due to its extensive land and feed requirements.

2.4.3. Social risk profiles

The S-LCA results (**Tables 5 and 6**) show a consistent comparative pattern of social risk exposure across all five assessed categories. Wool systematically exhibited the highest values in Labour Rights & Decent Work (1.59 mrheq), Health & Safety (0.43 mrheq), Society (0.75 mrheq), Governance (0.50 mrheq) and Community (0.65 mrheq), indicating the greatest potential exposure of workers and communities to social risks along its value chain. Hemp, in contrast, showed the lowest values across all categories, followed by lyocell, PLA and viscose, which occupied intermediate positions. The disaggregated results reported in the S-LCA sub-category table provided important insights into the drivers behind these aggregated risk profiles. In the Labour Rights & Decent Work category, higher risk levels for wool were linked to indicators such as low wages, migrant labour, child labour, limited social protection and weak enforcement of labour regulations, which were prevalent in several livestock-producing regions supplying global wool markets. For Health & Safety, the elevated wool score reflected increased exposure to occupational hazards and injuries in extensive farming and primary processing activities, which were generally more labour-intensive and less mechanised than fabric production in industrialised chemical plants. Within the Society and Governance categories, wool was associated with higher risks related to poverty and inequality, limited access to healthcare and education, corruption and weaker legal and institutional frameworks in upstream agricultural regions. These risks were far less pronounced for fabrics such as lyocell and PLA, whose supply chains were more strongly concentrated in industrialised regions with more robust governance and regulatory enforcement. The Community dimension further confirmed this pattern, with wool showing higher potential exposure to deficits in access to water, sanitation, electricity and basic local infrastructure. Overall, the S-LCA results indicated that fabrics derived from globally dispersed and labour-intensive agricultural systems, such as wool, tended to embed higher systemic social risks than fabrics produced in

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more capital-intensive and geographically concentrated industrial value chains. The detailed sub-category analysis strengthened the interpretability of the results and confirmed that the observed differences were not driven by a single indicator, but by consistent patterns across multiple social risk dimensions.

2.4.4. Economic and monetised environmental results

The LCC results show marked differences in production costs. Wool was the most expensive fabric (9.30 €), followed by PLA (5.35 €), viscose (4.87 €), lyocell (4.22 €) and hemp (1.42 €). Eco-Cost results, representing the monetised environmental damage, reinforced this ranking. Wool exhibited an Eco-Cost of 19.8 € per kg, which was an order of magnitude higher than all other fabrics: PLA 1.88 €, viscose 1.18 €, lyocell 1.03 €, and hemp the lowest value at 0.81 €. These results indicated that fabrics with higher environmental impacts also imposed substantially higher external costs on society.

3. Discussion

3.1. Integrated interpretation of results in the light of the state of the art

Recent literature consistently highlights that bio-based products do not automatically deliver sustainability benefits and that trade-offs across environmental, economic and social dimensions are pervasive in the bioeconomy (Zuiderveen *et al.*, 2023; Khanna *et al.*, 2024; Pérez-Hernández *et al.*, 2025). Reviews of circular bioeconomy practices further show that sustainability performance varies strongly depending on implementation scales, technologies and governance contexts (Bianchi *et al.*, 2024). At the methodological level, LCSA has been proposed as a conceptual response to this complexity, yet many practical applications remain fragmented and rely on poorly harmonised indicators (Bruno *et al.*, 2025; Zeug *et al.*, 2022; Marcinkowski & Haręża, 2025). The BIORADAR framework directly addresses these limitations by operationalising a fully harmonised, indicator-based and multi-method architecture. Compared with conventional LCSA applications, BIMMSF extends the analytical scope by explicitly integrating iLUC, Emergy and Eco-Cost within a harmonised inventory structure shared across the three sustainability pillars. Compared with broader multi-criteria or indicator-based sustainability frameworks, BIMMSF preserves method-specific interpretability and avoids collapsing heterogeneous results into a single composite score. However, unlike frameworks explicitly designed for decision analytics under uncertainty, the present proof-of-concept application does not yet include formal robustness testing or uncertainty propagation. The textile case study demonstrated that the joint application of LCA, iLUC, Emergy, S-LCA, LCC and Eco-Cost within this shared architecture enabled insights that are not accessible through single-method or loosely coupled LCSA applications. The explicit inclusion of land-use change, biophysical resource support and social risk screening provided a more systemic understanding of bio-based value chains than impact-based LCA alone. The results further confirmed that sustainability performance is not determined by material origin per se, but by the structure and governance of the underlying value chain. Wool, despite its renewable and natural character, emerged as the most problematic fabric across environmental, social and economic dimensions. High GHG emissions, extreme land occupation and iLUC-related climate effects were compounded by elevated social risks. These pressures were further mirrored by high production costs and Eco-Cost values. This finding reinforced earlier warnings that land-intensive agricultural bio-based systems can generate substantial sustainability burdens when globalised and scaled up (Gawel *et al.*, 2019; Ladu & Morone, 2024). In contrast, industrial bio-based fabrics such as lyocell and PLA exhibited lower land-related and social risks, but a higher dependence on industrial energy and material inputs. Hemp stood out as the only fabric performing well across all three sustainability pillars, combining low environmental pressure, high renewability in Emergy terms, low social risk exposure and low economic costs. Overall, these patterns illustrate a key insight of sustainability science: trade-offs are often driven by the interplay between land, labour and capital intensity rather than by the bio-based nature of materials alone (Chiarella *et al.*, 2023; Wang *et al.*, 2026). This system-level perspective is consistent with recent life-cycle studies emphasising the role of value chain organisation and end-of-life strategies in shaping sustainability outcomes (Patrizi *et al.*, 2026). By aligning biophysical, socio-economic and financial indicators within a single analytical space, the BIORADAR framework makes these interactions explicit and decision-relevant.

3.2. Integrated sustainability insights from multi-method triangulation

The added value of Emergy and multi-method triangulation becomes particularly evident when environmental, social and economic dimensions are analysed together. Importantly, Emergy indicators are not intended to be directly comparable, in a metric sense, with LCA midpoint impact indicators. Rather, they provide a complementary diagnostic lens by capturing the biophysical resource support and ecological work embodied in production systems, which remain only partially visible in conventional impact-based assessment. Within BIMMSF, convergent results across methods strengthen the identification of consistent sustainability hotspots, whereas divergent results do not invalidate the framework but instead reveal structural trade-offs that require contextual interpretation. In such cases, decision-making should not rely on automatic ranking, but on stakeholder judgement informed by the specific sustainability priority at stake, such as climate mitigation, land-use efficiency, renewability, social risk reduction or cost containment. As highlighted in previous studies (Pulselli *et al.*, 2015; Patrizi *et al.*, 2018; Santagata *et al.*, 2020), Emergy captures forms of environmental support that remain invisible in emission-based approaches. In this study, Emergy revealed the extremely high biophysical investment embodied in viscose and, to a lesser extent, wool, despite their relatively favourable performance in some LCA impact categories.

When combined with LCA and iLUC, Emergy linked emissions, land pressure and ecological support, allowing a more complete representation of bio-based sustainability, while the integration of S-LCA and Eco-Cost further extended this triangulation to social risks and economic externalities. The textile case study showed that fabrics perceived as low-impact from one perspective may be highly problematic from another: the disaggregated S-LCA results confirmed that the social risks associated with wool are not artefacts of aggregation, but reflected persistent vulnerabilities across labour conditions, health and safety, poverty, governance and community infrastructure, consistent with recent findings that many bio-based supply chains operate in regions with fragile institutions and weak labour protection (Fernández Ocamica *et al.*, 2024; Schipfer *et al.*, 2024). This interpretation is directly supported by the SHDB sub-category breakdown (**Table 6**), in which wool consistently records the highest values across multiple hotspot dimensions, including wage assessment, forced labour, excessive worktime, migrant labour, occupational hazards, injuries and fatalities, and poverty and inequality. In parallel, the environmental and economic disadvantages of virgin wool can be primarily associated with upstream fibre-production and feedstock-related inputs within the harmonised inventory, while downstream textile conversion steps appear less differentiating across the analysed cases. By contrast, fabrics produced in industrialised, capital-intensive settings tended to exhibit lower social risk exposure, even when their technological and financial intensity is higher, challenging the assumption that rural employment automatically implies social sustainability. From an economic perspective, the inclusion of Eco-Cost highlighted how apparent cost advantages often masked substantial environmental and social externalities, revealing that market prices alone provide a distorted signal of sustainability. Overall, this multi-method triangulation exposes structural blind spots of single-indicator assessments and underscores the need for geographically and economically sensitive evaluation frameworks in the bio-based textile sector.

3.3. Implications for industrial practice: the case of wool

The poor sustainability performance of conventional wool identified in this study reflected not an intrinsic limitation of the material, but the structural characteristics of its dominant linear and land-intensive production model. Virgin wool was tightly coupled to livestock farming, extensive land use and geographically fragmented supply chains, which jointly generated high greenhouse gas emissions, significant land-use change impacts and elevated social risks. This pattern is consistent with the existing literature, which shows that the agricultural phase - dominated by sheep farming - is responsible for most of the environmental burden of virgin wool, with its carbon footprint largely driven by enteric methane emissions and land use associated with grazing and feed production (Wiedemann *et al.*, 2016; Peri *et al.*, 2020). Conversely, comparative LCA studies demonstrate that circular industrial systems based on mechanically recycled wool can drastically reduce these impacts by decoupling fibre production from livestock-related emissions and land occupation (Bianco *et al.*, 2022). In contrast, recycled wool offers a fundamentally different sustainability pathway by decoupling textile production from agricultural land use and livestock emissions. The Prato textile district represents a particularly relevant example of this transition, having developed a mature industrial system for the mechanical recycling of wool garments into high-quality regenerated fibres and fabrics. Recent life cycle studies show that recycled wool from Prato achieves drastic reductions in GHG emissions, energy use and land occupation compared to virgin wool (Bianco *et al.*, 2022; Bianco *et al.*, 2023). Within the BIORADAR framework, this circular configuration would translate into much lower LCA, iLUC and Emergy burdens, as well as reduced social risk exposure, since production is concentrated in a regulated European industrial context. The contrast between virgin and recycled wool thus illustrates that sustainability is primarily a property of value-chain organisation rather than of materials themselves. For industry and policymakers, the Prato case demonstrates how investments in recycling infrastructure, design for recyclability and localised circular hubs can transform a high-impact bio-based fibre into a low-impact and socially more favourable solution, supporting the transition toward a genuinely circular bioeconomy.

3.4. Framework limitations and future development needs

Despite its advantages, the BIORADAR framework also reflects current limitations in sustainability assessment practice. As noted by Bianchi *et al.* (2024), sustainability indicators remain unevenly distributed across pillars, with environmental data generally more robust than social and economic information. The reliance on database-based S-LCA implies that results represent potential rather than site-specific social performance, and attribution issues remain in globalised supply chains. From an economic perspective, the simplified LCC applied in this study excludes CAPEX and therefore may underrepresent the total economic burden of more capital-intensive production pathways. This limitation should be considered when interpreting absolute cost differences across the analysed systems. At the current proof-of-concept stage, the textile application was designed to demonstrate cross-pillar integration and comparative hotspot screening rather than to provide exhaustive stage-level contribution analyses or formal sensitivity and uncertainty quantification. Accordingly, the present case study should not be interpreted as a full validation of the BIMMSF, but as an illustrative proof-of-concept application focused on methodological integration and hotspot screening. Formal sensitivity analysis, uncertainty propagation and robustness testing remain necessary steps for future applications intended for operational decision support. Within the present proof-of-concept application, the assumptions most likely to influence comparative outcomes are the generic iLUC emission factor, the unit-price assumptions used in simplified LCC, and the country- and sector-level mapping adopted in SHDB-based risk screening. These sources of model uncertainty were not subjected to formal analysis in the present study and should therefore be prioritised in future validation efforts. Future developments should therefore focus on integrating more granular, site-specific and digital monitoring data, particularly at the meso- and micro-scale, as well as improving dynamic modelling of land-use change, circular material flows and social conditions. The modular architecture of BIORADAR is designed to accommodate such extensions, supporting the gradual evolution towards more data-rich and decision-relevant sustainability assessments.

1. Conclusions

This paper presented the BIORADAR Integrated Multi-Method Sustainability Framework (BIMMSF) as an operational approach to life cycle-based sustainability assessment in industrial bio-based systems. By combining LCA with iLUC modelling and Emergy evaluation and integrating these environmental insights with Social LCA (risk-based screening) and an economic pillar including simplified LCC and Eco-Cost monetisation, the framework enables a harmonised and cross-dimensional interpretation of sustainability performance using consistent system boundaries, functional unit and underlying inventories. Importantly, BIMMSF does not collapse results into a single composite score; rather, it preserves the analytical meaning of each sustainability dimension while making trade-offs and potential blind spots explicit.

The proof-of-concept application to five textile fabrics (wool, PLA, viscose, lyocell, and hemp) demonstrated the added value of multi-method triangulation. Across the environmental pillar, wool consistently showed the highest burdens, with particularly critical land occupation and climate relevance once iLUC was included, confirming that land-intensive agricultural value chains can dominate sustainability profiles when assessed beyond direct emissions. Emergy further complemented impact-based LCA by revealing differences in biophysical resource support, highlighting the very high embodied ecological work for viscose compared to the other fabrics. Overall, hemp emerged as the only option performing well across the three sustainability pillars in the analysed sample, whereas wool represented the most problematic configuration, showing converging disadvantages across environmental impacts, social risk exposure and economic indicators. On the social pillar, the SHDB-based S-LCA consistently identified higher potential social risk exposure for wool across all five assessed categories, with the disaggregated sub-categories supporting the interpretability of this pattern and indicating that differences were not driven by a single indicator but by coherent risk signals across labour, governance and community dimensions. On the economic pillar, simplified LCC and Eco-Cost results reinforced the cross-pillar interpretation: the most environmentally burdensome value chain (wool) also exhibited the highest production costs and the highest monetised externalities, while hemp combined low costs with the lowest Eco-Cost. These findings reinforce a central implication of the BIORADAR approach: sustainability is not determined by the 'bio-based' nature of a material per se, but by the structure of the underlying value chain and, in SHDB terms, by the country- and sector-specific risk profiles embedded in upstream supply chains. Decision-making therefore requires integrated, indicator-based assessment to support hotspot screening and the prioritisation of improvement options, while formal sensitivity, uncertainty and robustness analyses remain necessary for fully operational decision support. Finally, the textile case study should be interpreted as a proof-of-concept application aimed at demonstrating the framework's integration logic and comparative hotspot-screening capacity, rather than as a full validation exercise or as a basis for definitive material rankings. It illustrates how BIMMSF can support decision-makers in identifying where improvements are most effective (e.g., decoupling impacts from land-intensive primary production through circular configurations). Future work should prioritise the progressive integration of more granular and site-specific data—particularly for social and economic dimensions—and the linkage with digital monitoring to move from risk screening and static inventories towards more decision-relevant, dynamic sustainability assessment in industrial bio-based systems. Beyond the methodological contribution discussed in this study, the BIORADAR project is actively translating the proposed integrated assessment framework into a set of interoperable digital tools aimed at widening access to sustainability information for bio-based value chains. These include a digital assessment platform supporting LCA, Eco-Cost and S-LCA evaluations. The platform integrates benchmarking and comparison functionalities, as well as synthetic datasets for decision support, and is further described in a dedicated methodological contribution currently under review. In parallel, BIORADAR also provides complementary tools for regulatory tracking and implementation guidance. By enabling structured data collection, digitalisation and dissemination of sustainability indicators, BIORADAR contributes to reducing information asymmetries that currently limit the market uptake of bio-based products. In this perspective, the framework and tools presented support not only improved sustainability assessment but also enhance the competitiveness of bio-based solutions with respect to conventional fossil-based alternatives.

Author Contributions

Conceptualization, M.M., D.S., D.F., H.I.; methodology, M.M., D.S., D.F., H.I.; formal analysis, M.M., D.S., D.F., H.I.; investigation, M.M., D.F., H.I., D.S.; resources, M.M., D.S., D.F., H.I.; data curation, M.M., D.F., H.I., D.S.; writing original draft preparation, M.M., D.S., D.F., H.I.; writing review and editing, M.M., D.F., D.S., H.I. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Supplementary Materials

Life Cycle Inventories (LCIs) used to calculate the environmental impacts linked to the manufacture of the textile products under study: hemp, lyocell, polylactic acid (PLA), viscose and wool.

Table S1. LCI for Hemp fabric

Hemp fabric – FU: 1 kg			
Phase	**Items**	**Value**	**Unit**
Cultivation	Seed	5.02E-03	kg
	Diesel for machinery	1.37E-02	kg
	Transport	5.13E+00	kgkm
	Ammonium nitrate (Fertiliser)	8.92E-03	kg
	Triple superphosphate (Fertiliser)	1.17E-02	kg
Harvesting	Diesel	4.66E-06	kg
	Lubricant	9.31E-08	kg
Breaking	Electricity	1.27E-01	kWh
Scutching	Electricity	2.71E-01	kWh
Hackling	Electricity	2.03E-01	kWh
Roving	Electricity	1.02E-01	kWh
Spinning	Electricity	1.04E+00	kWh
Weaving	Transport	3.25E+00	kgkm
	Electricity	9.58E-01	kWh
	Waste (incineration)	1.50E-02	kg
Finishing	Cleaning	1.60E-02	kg
	Silicone	2.90E-02	kg
	Chemical generic	5.00E-03	kg
	Transport	1.32E+01	kgkm
	Electricity	9.62E-01	kWh
	Waste (incineration)	1.50E-02	kg
Fabric	Transport	2.40E+00	kgkm
	Electricity	3.20E-02	kWh
	Waste (incineration)	1.00E-02	kg

Table S2. LCI for Lyocell fabric

Lyocell fabric – FU: 1 kg			
Phase	**Items**	**Value**	**Unit**
Preparation of spinning fluid	Auxiliaries	1.02E-02	kg
	Pulp	1.02E+00	kg
	Water	1.52E+00	kg
	Water	2.54E+00	kg
	N-Methylmorpholine N-oxide (NMMO)	4.06E-03	kg
	Electricity	7.62E-01	kWh
	Cross-linking agent	3.05E-03	kg
	Electricity	1.02E-01	kWh

Solvent recovery	Oil for spinning	8.13E-04	kg
	Water	2.54E-01	kg
	Sodium hydroxide - NaOH	2.03E-01	kg
	Hydrochloric acid - HCl	1.52E-01	kg
	Natural gas	2.11E-01	kg
	Water	4.06E+00	kg
	Electricity	5.08E-02	kWh
Fibre finishing	Oil for spinning	2.24E-03	kg
	Softened water	6.10E+00	kg
	Natural gas	3.17E-01	kg
	Water	6.10E+00	kg
	Electricity	9.14E-01	kWh
	Transport	2.78E+02	kgkm
Weaving	Electricity	9.58E-01	kWh
	Waste (incineration)	1.50E-02	kg
Finishing	Cleaning	1.60E-02	kg
	Silicone	2.90E-02	kg
	Chemicals	5.00E-03	kg
	Transport	1.00E+01	kgkm
	Electricity	9.62E-01	kWh
	Waste (incineration)	1.50E-02	kg
Fabric	Electricity	3.20E-02	kWh
	Waste (incineration)	1.00E-02	kg

Table S3. LCI for PLA fabric.

PLA fabric – FU: 1 kg			
Phase	**Items**	**Value**	**Unit**
Drying	Polylactide	1.07E+00	kg
	Transport	2.14E+02	kgkm
	Electricity	1.37E-01	kWh
Spinning	Electricity	8.03E+00	kWh
Weaving	Electricity	9.58E-01	kWh
	Waste (incineration)	1.50E-02	kg
Finishing	Cleaning	1.60E-02	kg
	Silicone	2.90E-02	kg
	Chemicals	5.00E-03	kg
	Transport	1.00E+01	kgkm
	Electricity	9.62E-01	kWh
	Waste (incineration)	1.50E-02	kg
Fabric	Electricity	3.20E-02	kWh
	Waste (incineration)	1.00E-02	kg

Table S4. LCI for Viscose fabric.

Viscose fabric – FU: 1 kg			
Phase	**Items**	**Value**	**Unit**
Preparation of spinning fluid	Pulp	1.02E+00	kg
	Sodium hydroxide - NaOH	3.05E-01	kg
	Water	1.02E+01	kg
	Sodium hydroxide - NaOH	1.52E-01	kg
	Water	2.05E+00	kg
	Carbon disulfide - CS_2	8.43E-02	kg
	Sulphonate	9.86E-03	kg
	Sodium hydroxide - NaOH	1.02E-01	kg
	Water	8.13E+00	kg
	Electricity	3.05E-01	kWh
	Coal	4.80E-01	kg
Treatment before spinning	Water	1.02E+01	kg
	Water	1.02E+01	kg
	Electricity	1.42E-01	kWh
	Water	2.03E+01	kg

The spinning process Fibre finishing	Sulfuric acid - H_2SO_4	7.62E-01	kg
	Sulfuric acid - H_2SO_4	2.54E-02	kg
	Zinc sulfate - $ZnSO_4$	5.59E-02	kg
	Electricity	1.02E-01	kWh
	Sodium hydroxide - NaOH	5.08E-02	kg
	Sulfuric acid - H_2SO_4	2.54E-02	kg
	Natural gas	3.71E-01	kg
	Water	7.14E+00	kg
	Oil for spinning	2.54E-03	kg
	Electricity	3.05E-01	kWh
	Transport	6.14E+02	kgkm
Weaving	Electricity	9.58E-01	kWh
	Waste (incineration)	1.50E-02	kg
Finishing	Cleaning	1.60E-02	kg
	Silicone	2.90E-02	kg
	Chemical generic	5.00E-03	kg
	Transport	1.00E+01	kgkm
	Electricity	9.62E-01	kWh
	Waste (incineration)	1.50E-02	kg
Fabric	Electricity	3.20E-02	kWh
	Waste (incineration)	1.00E-02	kg

Table S5. LCI for Wool fabric

Wool fabric – FU: 1 kg			
Phase	Items	Value	Unit
Antistatic	Glycerine	1.26E-02	kg
	Chemical	8.30E-03	kg
	Transport	4.18E+00	kgkm
	Water	6.23E-02	kg
PP Reel	Polypropylene (PP)	3.30E-02	kg
	Transport	6.60E+00	kgkm
	Injection moulding	3.26E+00	kWh
Spinning	Sheep fleece	1.13E+00	kg
	Transport	2.43E+02	kgkm
	Electricity	2.40E+00	kWh
	Waste (incineration)	1.04E-01	kg
Winding	Transport	6.60E+00	kgkm
	Electricity	2.80E-01	kWh
	Waste (incineration)	1.00E-02	kg
Warping	Electricity	7.40E-02	kWh
Weaving	Electricity	9.58E-01	kWh
	Waste (incineration)	1.50E-02	kg
Finishing	Cleaning	1.60E-02	kg
	Silicone	2.90E-02	kg
	Chemicals	5.00E-03	kg
	Transport	1.00E+01	kgkm
	Electricity	9.62E-01	kWh
	Waste (incineration)	1.50E-02	kg
Fabric	Electricity	3.20E-02	kWh
	Waste (incineration)	1.00E-02	kg