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Development of a Life Cycle Sustainability Assessment Framework for Hemp-Based Building Materials in Australia

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Abstract

The construction industry, a cornerstone of global economic and social progress, is under increasing pressure to adopt sustainable practices due to its significant environmental footprint. Industrial hemp (*Cannabis sativa* L.) has gained attention as a renewable material for building applications, offering potential reductions in greenhouse gas emissions and resource consumption. However, its broader sustainability performance remains underexplored. This study develops a comprehensive Life Cycle Sustainability Assessment (LCSA) framework to evaluate the environmental, economic, and social implications of hemp-based building materials in Australia. The framework integrates environmental life cycle assessment, life cycle costing, and social life cycle assessment based on ISO 14040-44 standards. Using a participatory approach, 19 indicators were identified relevant for the sustainability assessment of hemp-based materials through consultation with 30 stakeholders across the construction, hemp industries, and academia. By addressing critical gaps in methodology, this study provides a robust tool for stakeholders to optimise the sustainability performance of hemp-based building materials and advance net-zero construction practices.

Keywords
Life cycle sustainability assessment; triple bottom line sustainability objectives; sustainable materials; hemp-based building materials; hemp-based boards

1. Introduction

The construction industry is a cornerstone of modern development, shaping infrastructure, housing, and economic progress [1]. Globally, the sector accounts for approximately 10% of gross domestic product (GDP) and provides employment to over 100 million individuals [2]. However, its social and economic benefits have come at a significant cost to the environment. The construction sector is one of the largest contributors to greenhouse gas (GHG) emissions, responsible for 37% of global emissions [3], and its operations aggravate challenges such as plastic pollution [4], resource depletion and waste generation [5]. As the global demand for infrastructure and housing rises, there is a pressing need to transition towards sustainable building materials that mitigate environmental impact while improving economic and social performance throughout the building's life cycle.

Industrial hemp (*Cannabis sativa* L.) has emerged as a potential alternative for conventional materials that are energy and resource-intensive. Largely due to its rapid growth, high carbon sequestration capacity, mechanical and thermal properties, this material is highly suitable for non-structural building applications [6]. Hemp-based materials can be utilised in different building applications, such as insulation, fibre-reinforced panels, and particleboards. These alternative materials offer advantages over conventional substitutes in terms of thermal efficiency, carbon footprint, and recyclability [7, 8]. Most of the environmental life cycle assessment (ELCA) studies have confirmed that the hemp-based composites generally exhibit lower life cycle GHG emissions compared to traditional materials such as polyisocyanurate boards, wood wool boards [9] and gypsum plasterboards [10]. However, sustainability research on hemp-based materials has primarily focused on environmental impacts, with limited emphasis on the broader sustainability profile, including economic and social considerations [11]. This limitation has led to significant research gaps, particularly in assessing the market-competitiveness of hemp-based materials in large-scale applications and their impact on labour markets and health and safety standards [12].

In the case of Australia, the construction sector presents unique sustainability challenges. It accounts for 18% of national GHG emissions [13], consumes approximately 25% of the country's total materials [14] and generates over 38% of landfill waste [15]. The country's per capita material footprint is among the highest in the world, four times the global average, placing a significant pressure on natural resources and landfill infrastructure. Simultaneously, the Australian hemp industry is expanding, presenting opportunities for locally sourced, low-carbon feedstocks for material production [16, 17]. Although research has supported the use of hemp-based materials to mitigate life cycle GHG emissions in buildings, comprehensive assessments of its economic viability and social acceptance within the Australian market are limited [10].

Efforts to integrate economic performance indicators into sustainability assessments could potentially address some of these gaps. Rivas Aybar, John [18] used an eco-efficiency framework to compare the environmental and economic performance of non-structural hemp-based boards with gypsum plasterboards. The study found that the use of electricity generated from the photovoltaic panels can enhance the eco-efficiency of hemp-based materials in Australia. Whilst this study provided valuable insights into the cost-effectiveness of hemp products, it did not fully incorporate the life cycle costing (LCC) methodology to assess long-term financial viability of these novel materials. Furthermore, studies evaluating the economic sustainability of hemp-based composites ignored the impact of market dynamics, supply chain constraints, and financial incentives that could either facilitate or hinder large-scale adoption [9, 19, 20].

Social sustainability, a critical yet often neglected component of sustainability assessments, remains one of the most underexplored aspects of hemp-based materials [12]. Unlike ELCA and LCC, which have established methodologies for quantifying environmental and economic impacts, social life cycle assessment (SLCA) is still evolving and lacks standardised indicators suitable for assessing the impacts of building materials across the whole life cycle [21]. Key social considerations such as job creation, occupational health and safety, fair labour practices, and community acceptance have been minimally addressed in existing literature [22]. The studies on hemp value chains have highlighted the potential for rural economic development and employment generation, particularly in agricultural and processing sectors [2]. However, the extent to which hemp-based materials contribute to social sustainability metrics, particularly in regions with emerging hemp industries such as Australia, remains largely unknown [23].

A comprehensive sustainability assessment necessitates methodologies that can quantify and compare the triple bottom line (TBL) of sustainability, encompassing environmental, economic, and social aspects, of different products that serve the same purpose [24]. The life cycle sustainability assessment (LCSA) provides a holistic framework for assessing and comparing the TBL performance of alternative products across their life cycle to identify hotspots and determine strategies to improve sustainability outcomes. This requires careful selection of location and product-specific TBL performance indicators [25, 26].

The LCSA framework was deemed essential to achieve a significant transition towards sustainability in the built environment, however, its use is still scarce in this realm [2]. In Australia, Janjua, Sarker [25] integrated multicriteria assessment techniques involving a thorough literature review as well as the expert surveys at the local level to determine the Australian-based TBL indicators for assessing sustainability performance of residential buildings. However, it is important to note that while these indicators offered a robust framework for evaluating residential buildings, they may not be directly applicable to other aspects on the construction arena [26]. To ensure the relevance and accuracy of sustainability assessments for hemp-based materials, a products and region-specific approach is needed, incorporating indicators tailored to Australia's TBL conditions.

Considering the research gaps mentioned in the previous paragraphs, this study aims to develop a tailored LCSA framework specifically for evaluating hemp-based building materials in Australia. The central research question guiding this study was whether a region-specific LCSA framework can effectively assess the TBL performance of hemp-based building materials and how the results of the LCSA analysis compare hemp-based materials with conventional alternatives available in Australia. It is important to note that the TBL performance of same materials varies across regions due to differences in socio-economic conditions, geography, climate, and resource utilisation [25].

To address these complexities, the study engaged key industry stakeholders based in Australia. These participants contributed to the selection and validation of product- and location-specific TBL indicators, ensuring that the analysis captured sector- and region-specific concerns [27]. Given the diversity of perspectives and interests among stakeholders, a multicriteria analysis based on a participatory approach was employed [24, 28]. This methodology represents an innovative aspect of the research, as it is the first of its kind specifically designed for hemp-based building materials within an LCSA framework.

This LCSA framework used the ELCA, LCC, and SLCA tools to estimate the region-specific indicators of environmental, economic, and social bottom lines of sustainability, respectively [21]. The LCSA results were integrated into a sustainability performance score for material, enabling direct comparisons with conventional alternatives. This approach supports policymakers, manufacturers, and construction professionals in assessing building materials and identifying opportunities for improvement. The broader objective was to develop a sustainability assessment tool that facilitates industry adoption of better alternatives, ensuring decision-makers in the construction sector have access to reliable data for informed material selection.

2. Theoretical Framework for the Development of the Life Cycle Sustainability Assessment for Hemp-Based Building Materials

The theorical framework for the development of the LCSA for hemp-based building materials in Australia was based on the methodology proposed by Kloepffer [29] and enhanced by UNEP/SETAC [21]. The UNEP/SETAC taskforce published the procedure for integrating the three life cycle assessment tools into an overarching LCSA framework as follows [29]:

$$LCSA = ELCA + LCC + SLCA \tag{1}$$

This LCSA formulation enables a system perspective where these tools are executed separately to assess the TBL performance of a product [30]. Each of these three methodologies follows four steps: definition of the goal and scope; life cycle inventory analysis (LCI); life cycle impact assessment (LCIA); and, life cycle interpretation [31, 32] as shown in Figure 1. These four stages will be detailed be in Section 3. ELCA, SLCA and LCC calculates environmental, social and economic indicators of sustainability and then the LCSA framework enables the integration of these TBL indicators into one single sustainability score for each product or specification.

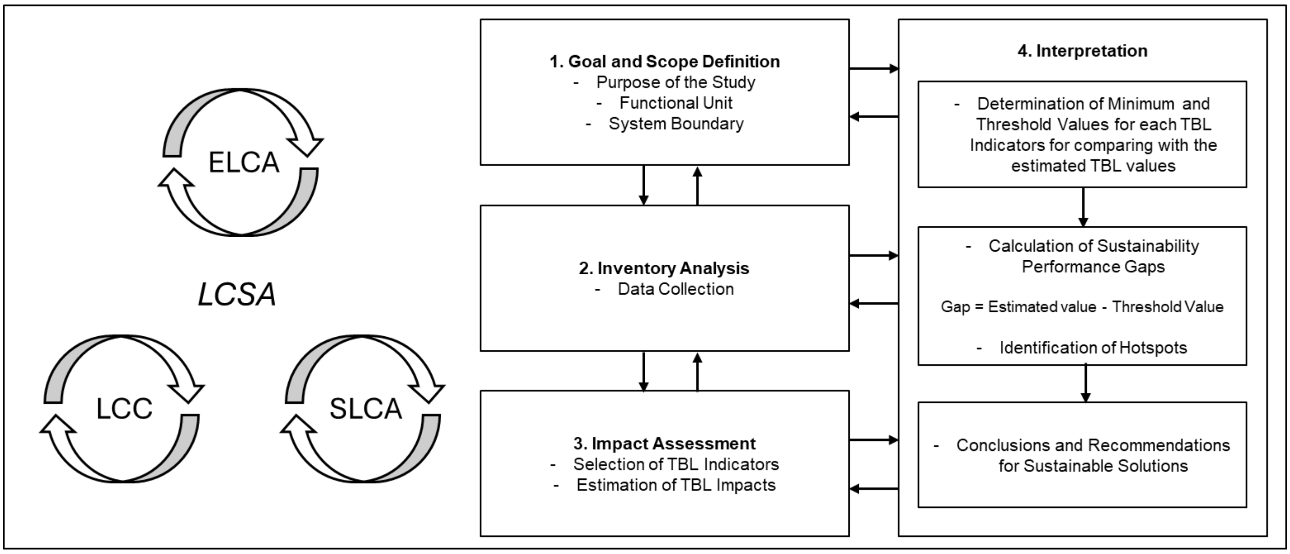


Figure 1 Life cycle sustainability assessment framework, adapted from ISO [31], ISO [32], UNEP/SETAC [21] and Biswas and John [24].

2.1 Environmental Life Cycle Assessment

The ELCA is a systematic framework for quantifying the inflows and outflows of a product system that contribute to environmental impacts [33]. International standards recommend a comprehensive set of impact categories to assess the environmental performance of buildings, including global warming, acidification, eutrophication, ozone depletion, land use, water use, and biodiversity [34]. ELCA provides valuable insights that enable decision-makers to take informed actions to mitigate these impacts [35].

2.2 Life Cycle Cost

The LCC is considered the economic counterpart of ELCA and represents the economic dimension of LCSA [21, 36]. Traditionally, LCC has been employed to calculate and compare the life cycle costs of different product alternatives, based on manufacturing, utilisation, maintenance, and end-of-life costs. However, integrating additional economic indicators allows for a more comprehensive assessment within LCSA. A wide range of indicators are available to LCSA practitioners for assessing economic aspects beyond costs, ideally from both a system-wide and end-user perspectives [33]. Commonly used impact categories in recent LCC-based studies include profitability, productivity, innovation, stability, customer value, and autonomy [37].

2.3 Social Life Cycle Assessment

The SLCA aims to comprehensively assess impacts of a product on human welfare throughout its life cycle [38]. This methodology assists decision-makers in identifying strategies offering the most favourable social outcomes for stakeholders in the supply chain including for workers, suppliers, consumers, and society as a whole [39]. Unlike ELCA and LCC, which primarily rely on quantitative data, SLCA actively involves stakeholders across a product's life cycle to obtain qualitative feedback [33]. While ELCA and LCC have well-established methodologies for quantifying environmental and economic impacts, SLCA is still evolving and lacks standardised indicators for assessing the social impacts of building materials across their life cycle [21].

2.4 Life Cycle Sustainability Assessment

The LCSA framework required the selection of region- and product-specific environmental, economic and social performance indicators, which were estimated using the ELCA, LCC and SLCA, respectively. The methodology used for the selection of TBL indicators consisted of five steps including literature review for primarily selecting the indicators, followed by the selection of respondents who were interviewed to validate, weight and aggregate these indicators [24]. The indicators selected followed a hierarchical structure with LCSA at the first level of the hierarchy (Figure 2). The second level consisted of the sustainability objectives, where each objective was divided into head performance indicators (HPI). Each HPI was the aggregation of key performance indicators (KPIs) which constituted the lowest level of the hierarchy.

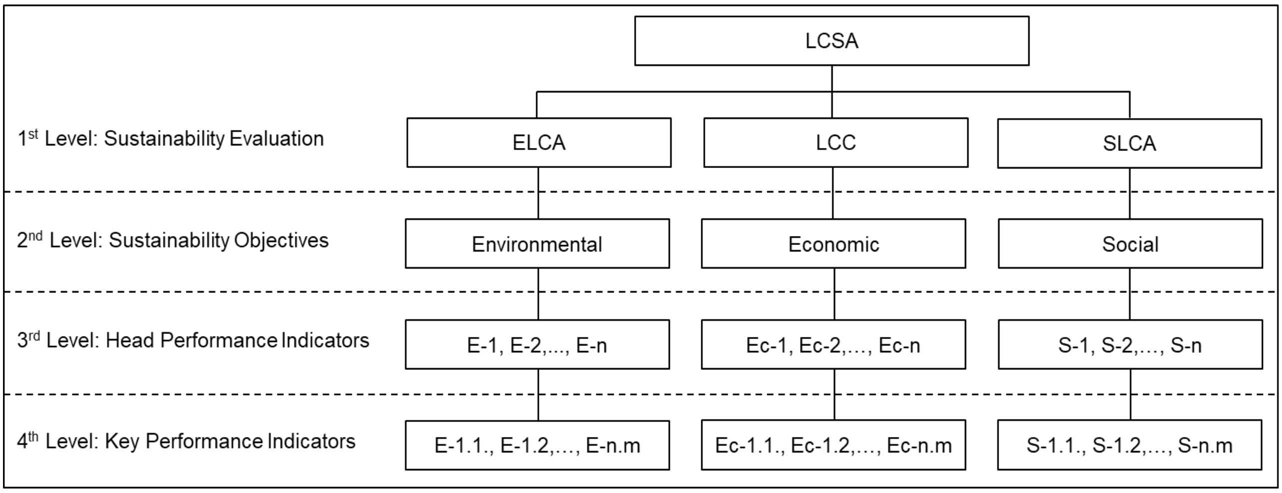


Figure 2 Hierarchical structure of the LCSA framework, adapted from Biswas and John [24].

3. Framework for the Life Cycle Sustainability Assessment of Hemp-Based Building Materials

3.1 Goal and Scope Definition

The goal of the study was to build a region-specific LCSA model for hemp-based building material production. The LCSA framework aimed to evaluate the TBL implications of producing these emerging building materials in Australia. The functional unit was determined based on the primary function of the product under study, mechanical strength for the case of these non-structural building products. Accordingly, the functional unit was specified as 1 MPa equivalent of mechanical strength of hemp-based material. The system boundary included all production stages (cradle-to-gate), as follows:

- Pre-farm: Production of agricultural inputs and the transportation of these inputs to the farm.
- On-farm: Agricultural machinery operation and transportation of hemp stalks from the farm to the processing plant.
- Post-farm: Indoor transportation of raw materials, mechanical process of the stalks, binder production, blending, and pressing.

3.2 Life Cycle Inventory Analysis

In LCSA, the LCI is the quantification of elementary flows and conditions of the product system with respect to the functional unit and system boundary [30, 40]. Elementary flows refer to the assessment of inputs, such as materials and energy, and outputs, including emissions to air, water, or land. The conditions include economic and social aspects, e.g. production costs, local employment, and worker rights.

Data sources for the inventory analysis of hem-based boards production included primary and secondary data. Primary data for ELCA, LCC and SLCA was collected through direct quantitative and qualitative measurements. Secondary data was obtained from public and commercial databases such as the Australian National Life Cycle Inventory Database (AusLCI) for environmental aspects and regional statistical databases for the economic and social aspects.

3.3 Life Cycle Impact Assessment

Using the LCI data, the LCIA aims to calculate and evaluate the magnitude of TBL impacts of the product system. This required the previous selection of TBL indicators relevant to the product and region under investigation [41]. As mentioned above, this framework followed the five-step methodology described by Biswas and John [24] for ascertaining the TBL indicators for a particular product (Figure 3). Each step is described in the following sections.

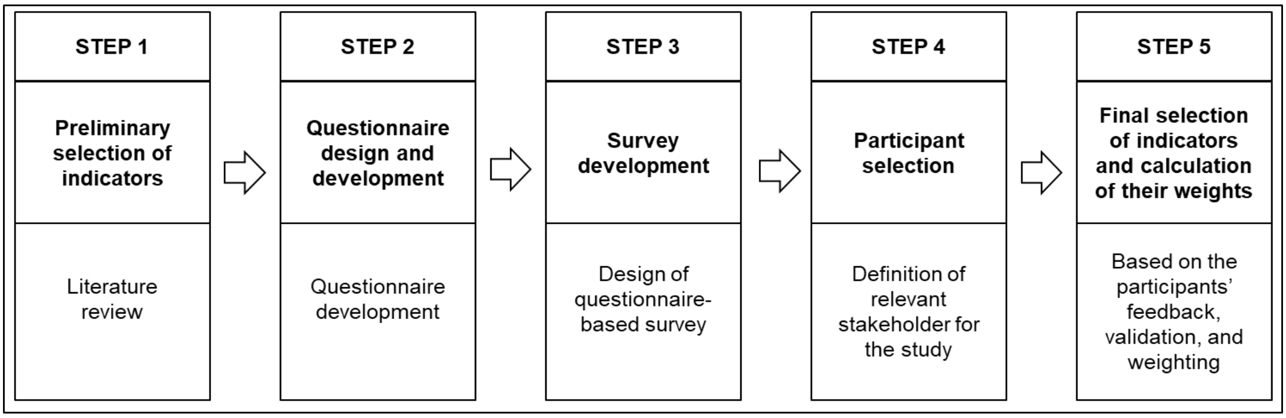


Figure 3 Development of relevant TBL indicators. Adapted from Biswas and John [24].

3.3.1 Step 1. Preliminary Selection of Indicators

The preliminary selection of KPIs and HPIs was made through literature review, which consisted of comprehensive analysis of existing local and overseas literature on environmental, economic and social impacts of the production of hemp-based materials. Table 1 presents the preliminary list of 18 KPIs which were classified under six HPIs. The description of each KPI has been explained in the following section.

Table 1 Preliminary selection of TBL KPIs for the assessment of hemp-based materials.

Sustainability objectives		Head performance indicator (HPI)		Key performance indicator (KPI)	
E	Environmental	E-1	Ecosystem	E-1.1	Global warming
				E-1.2	Acidification
				E-1.3	Eutrophication
				E-1.4	Terrestrial ecotoxicity
				E-1.5	Freshwater ecotoxicity
				E-1.6	Marine ecotoxicity
		E-2	Human health	E-2.1	Human toxicity
				E-2.2	Ozone layer depletion
		E-3	Resources	E-3.1	Energy consumption
				E-3.2	Land use
				E-3.3	Water use
Ec	Economic	Ec-1	Producer perspective	Ec-1.1	Investment
				Ec-1.2	Profit margin
				Ec-1.3	Carbon offset
				Ec-1.4	Production cost
S	Social	S-1	Community	S-1.1	Job creation & employment
		S-2	Workers	S-2.1	Health & safety/Production
				S-2.2	Health & safety/Processing

E. Environmental objective:

E-1. Ecosystem

E-1.1. *Global warming:* As mentioned above, infrastructure activity plays a critical role in global warming accounting for over one third of worldwide GHG emissions [3]. The use of carbon-intensive materials i.e., cement, steel, and aluminium, contributes to a large share of these emissions. Additionally, agricultural production, which is the first stage for producing hemp-based materials, is responsible for 10 to 14% of total global GHG emissions [42]. Global warming accelerates the intensity and frequency of extreme events, such as surface and underwater heatwaves, floods, droughts, storms, and wildfires. This indicator has been the most studied in the existing literature [43-45]. As recommended by the Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia [46], the unit of measurement for this indicator is kilograms (kg) of CO_2-equivalents (eq) per MPa of hemp-based building material.

E-1.2. *Acidification:* Nitrogen (N) is a vital nutrient for plant growth [47]. The human population, with a clear upward trend, has led to the growing use of N fertilisers to increase agricultural production. Microbial activity of agricultural soils account for a large proportion of global nitrous oxide (N_2O) releases to the atmosphere which is one of the major stressors to acidification [47]. In Australia, the agricultural sector releases around 80% of N_2O emissions [48]. Acidification poses a burden to freshwater and marine biodiversity, mainly coral reefs and associated ecosystems, and to the ability of oceans to act as a natural sink of GHG [49]. Acid deposition also has corrosive effects on buildings, monuments, and historical artifacts. Acidification is expressed in kg SO_2-eq per MPa of hemp-based material [46].

E-1.3. *Eutrophication:* Along with N, another important nutrient for crop development is phosphorus (P) [50]. Growing stress on agricultural productivity has resulted in the rapid increase of P on the environment leading to eutrophication [51]. Eutrophication refers to the existence of excessive input of nutrients in freshwater and marine systems [52]. When nutrients such as P and N are excessively added to water systems, they lead to proliferation of algae and aquatic weeds. The potential consequences of eutrophication are unpleasant odours or taste, biodiversity loss, and the production of chemical compounds toxic to mammals, including humans that affected trough the food chain. Eutrophication is measured in kg phosphate (PO_4)-eq. per MPa of material [46].

E-1.4, E-1.5 and E-1.6. *Terrestrial, freshwater and marine ecotoxicity:* Agricultural inputs, mainly pesticides, can contain substances that have potential impact on non-human species [53]. Various pesticides are persistent in the environment and can have negative consequences on non-target organisms. For instance, insecticide usage has been found to be the main driver for global pollinator decline, affecting biodiversity and ecosystem services [54]. Agricultural inputs can impact aquatic and terrestrial ecosystems, therefore, ecotoxicity usually covers freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity [55]. Terrestrial, freshwater and marine ecotoxicity is accounted in kg 1.4-dichlorobenzene (DCB)-eq. per MPa.

E-2. Human health

E-2.1. *Human toxicity:* Chemical or organic agricultural inputs, mostly pesticides, can contain substances that have the potential to harm human health [53]. These substances are usually distinguished between carcinogens and non-carcinogens [56]. In Australia, the average pesticide use has increased twofold since 1990, rising from under 0.4 kg/ha on average to more than 1.0 kg/ha in 2016 [57]. Some pesticides can be persistent and bioaccumulate in non-target organisms, including humans, especially considering that a significant amount of the applied chemicals are not uptake by the crop and remain in the environment [54]. Human toxicity is measured in kg 1.4-dichlorobenzene (DCB)-eq. per MPa.

E-2.2. Ozone layer depletion: In addition to contribute to global warming, N_2O is also a potent ozone layer depleting compound [58]. The stratospheric ozone layer prevent ultraviolet (UV) radiation from the sun entering the atmosphere [49]. Its thinning has well-known adverse effects on human health and ecosystems. This indicator is expressed by kilograms of chlorofluorocarbon-11 (CFC11)-eq. per MPa [46].

E-3. Resources

E-3.1. Energy consumption: Buildings and construction account for over 40% of energy consumption [59]. Non-renewable energy sources such as fossil fuels cause higher environmental impacts compared to renewable sources like wind, hydro or solar. Furthermore, fossil fuels are rapidly reaching their biophysical limit. Australia's situation is concern as the energy generation is dominated by non-renewables resources [60]. Energy consumption is measured in megajoules (MJ) per MPa.

E-3.2. Land use: Agricultural land covers 37% of the global ice-free terrestrial area [61], making it the world's largest land use [62]. Agricultural expansion and intensification is a major driver of land use changes, which can accelerate biodiversity loss and environmental changes [49]. Furthermore, the conversion of natural ecosystems to croplands is the dominant global cause of biodiversity loss [63]. In Australia, farming activities accounts for over 50% of the nation's landmass use and it is expected to expand further [57]. In addition, Australia is considered as one of the hotspot regions in the world, where high biodiversity will be most threatened by agriculture by 2030 [64]. The land use indicator measures the use of land area for a certain period of time [65]. It is measured in ha. a. (hectare per year) per MPa.

E-3.3. Water use: Agricultural production constitutes the largest proportion of Australia's water use, with industrial and residential activities often representing the second and third most significant demand, respectively [66]. As a predominantly arid country, Australia faces extreme water stress [67]. Water use contributes to water scarcity and pollution, which poses a major threat to human and natural systems. The water use indicator accounts for the amount of water extracted from the environment by anthropic activities [68]. It is measured based on m^3-H_2O per MPa.

Ec. Economic objective:

Ec-1. Producer perspective

Ec-1.1. Investment: Investment measures the deployment of capital towards the production of hemp-based building materials, which is expected to generate a financial return over time. Investment is critical to ensure the long-term financial sustainability of a company [69]. Hemp-based materials have been manufactured and marketed for thousands of years; however, the modern hemp industry presents various investment challenges including limited market access, understanding of the hemp agronomy, uncertainties associated with the regulation, and the cost-competitiveness of hemp relative to other potential feedstocks [70, 71]. Investment is measured in AUD per MPa of hemp-based material per year.

Ec-1.2. Profit margin: Profit margin is a widely used financial metric that indicates the profitability of a company [72]. Reported as a percentage, it shows the share of a company's sales revenue retained as profit after deducting capital and operational costs. This indicator is measured and reported as a percentage.

Ec-1.3. Carbon offset: Carbon offset refers to the amount of atmospheric carbon sequestered in hemp biomass during plant growth, subtracted by the CO_2eq released throughout its life cycle [73]. The carbon sequestration of hemp can be estimated based on dry weight yield [74], whereas the life cycle CO_2eq emissions can be estimated through the ELCA approach [10]. The carbon offset from hemp farming is expected to gain official recognition by the government as Australian Carbon Credit Unit (ACCU) [75]. One ACCU represents one tonne of CO_2eq offset that would have otherwise been released into the atmosphere. The economic value of ACCUs fluctuates based on supply and demand in the carbon market. This indicator is expressed in terms of AUD per MPa of hemp-based material.

Ec-1.4. Production costs: Gaining insight into the cost structure of new materials is essential for making informed decisions that align affordability, productivity, and sustainability goals in construction projects [76]. Considering these factors is critical to encourage adoption of hemp-based materials without compromising construction efficiency. The production costs of hemp-based materials will be determined using the LCC tool according to ISO 15686-5:2017. The measurement of this indicator is expressed in terms of AUD per MPa of hemp-based material.

S. Social objective:

S.1. Community

S-1.1. Job creation an employment: The Australian hemp industry, although in its early stages, is rapidly expanding, potentially boosting employment in this emerging sector throughout its entire supply chain including pre-farm, on-farm and post-farm stages [11, 17]. Employment is crucial for individual well-being, economic stability, and improve the living standard, fostering physical and mental health and social interactions [77]. Job creation and employment is estimated by totalling the full-time equivalent (FTE) roles over a year.

S.2. Workers

S-2.1. Health and safety/Production: Work health and safety (WHS) requirements in Australia aim to prevent injuries in the workplace, particularly in high-risk sectors like agriculture, where working alone or in remote areas increases WHS risks [78]. Herbicide use in industrial hemp production poses health risks to farmers labour, such as neurotoxicity, allergies, and respiratory issues [12]. Hemp pollen can also trigger allergic skin reactions and asthma-like symptoms [79]. This indicator is reported as the incidence rate (serious claims per employees) per year at the hemp farming facilities.

S-2.2. Health and safety/Processing: At hemp processing facilities, workers face exposure to diverse biologically active hemp dusts, encompassing organic and inorganic elements like plant particles, virus, bacteria, mycotoxins, pollen, insects, and compost [79]. This exposure can result in severe health issues, including respiratory problems. The labour-intensive nature of hemp processing contributes to musculoskeletal disorders, with risks heightened by factors like improper posture, noise, and unsafe working environments [12]. This indicator is calculated by taking the incidence rate (serious claims per employees) over a year at the hemp processing facilities.

3.3.2 Step 2. Questionnaire Design and Development

It was accepted that the literature review selected TBL KPI that were indicative of current thought and analysis of environmental, economic and social impacts of the production of hemp-based materials but may not necessarily reflect the full and true costs of those impacts. Alternative models of indicator selection were then considered including an additional stakeholder and expert survey' based weighting of the indicator set. This extended analysis was deemed necessary in order to highlight the increasingly dynamic nature of TBL indicator development globally and the increasingly important role of future focused stakeholder leadership and expert advice in this sustainability transition. Increasing levels of global development of mandatory sustainability reporting are suggesting a new ethic is emerging that is demanding more accountability, in particular in relation to future focused environmental and social impact assessment [80]. This paper use of hemp stakeholders and sustainability experts to validate, provide feedback and weight a revised TBL KPI set that was focused on more important sustainability metrics than just those metrics particularly relevant to hemp production is an effort to reflect these increasing pressures on sustainability assessment on this analysis.

The main tool used to collect the hemp stakeholders and sustainability experts' views was an anonymous questionnaire-based survey. This type of survey has proven advantageous due to perceived anonymity, which fosters unbiased responses [2]. The survey structure was divided into the following sections:

i. Introduction: This section outlined the research objectives, funding sources, investigators, target demographic, and anticipated outcomes. Prior to proceeding to the following parts, participant consent was mandatory. Participants were also requested to write down their location to verify if they were based in Australia.
ii. Preliminary indicators: This part contained closed and open-answer questions. The closed ended questions were designed to determine whether the preliminary KPIs were relevant for the participants and, if so, their level of importance had to be answered. The open-ended questions were designed to allow participants to briefly explain the reasons why they considered the KPI as not relevant.
iii. Additional indicators: Like the previous section, this contained closed and open-ended questions as it the participants to suggest additional KPIs and their level of importance.

Prior to launching the survey, the questionnaire was tested by two researchers from the Sustainable Engineering Group (SEG) at Curtin University. Feedback was gathered on the applicability of the questions, structure of the survey, and its capacity for producing meaningful outcomes. The feedback was used to revise and improve the questionnaire.

3.3.3 Step 3. Online Survey Development

Google Forms was selected as the online survey distribution platform because was cost-effective and had the ability to reach a diverse groups of audience [25, 41]. The responses collected via Google Forms were easily viewed online and exported to MS Excel.

3.3.4 Step 4. Participant Selection

The objective of the participatory approach was to consider and build consensus among a broad range of stakeholders with different perspectives [27]. Stakeholder participation in the selection, weighting, and aggregation of TBL indicators was important for increasing the reliability and acceptability of the LCSA outcomes [81]. Hence, the choice of stakeholders was crucial in the process of building the LCSA framework for hemp-based building materials [24].

The choice of participants was based on the stakeholder theory in which stakeholders are defined as individuals that can affect, or be affected by, the industry's activities [82]. Potential participants were further subjected to the evaluation of the stakeholder's attributes: power, legitimacy and/or urgency [83]. Accordingly, the following were considered as potential participants for this research:

- Individuals who can impact the production of hemp-based boards.
- Individuals who are impacted by the production of hemp-based boards.
- Individuals who support the production of hemp-based boards.
- Individuals who have a legitimate moral or legal claim on the production of hemp-based boards.
- Individuals who are considered experts on sustainability.

Aligned with these criteria, three different stakeholder categories were selected: i) construction industry; ii) hemp industry; and, iii) government and academia, in Australia. The choice of Australia-based stakeholders made the LCSA framework regionally relevant to address the sustainability challenges with hemp-based materials produced in this country. Table 2 shows the examples of the three stakeholder categories.

Table 2 Stakeholder categories.

N	Categories	Examples
1	Construction industry	Project managers Investors Sustainability consultants
2	Hemp industry	Seed producers Farmers Workers
3	Government & academia	Extensionists Hemp researchers Sustainability researchers

The online survey took place between March 2023 and January 2024, following ethics approval (N HRE2023-0053) obtained from Curtin University's Research Office. The research aimed to obtain ten responses from each stakeholder category to maintain a balance between categories. Initially, 60 potential participants (20 from each stakeholder group) were invited via email and social media platforms for professionals (LinkedIn). The invitations contained the details about the main investigators, funders, university affiliation, objectives, survey timeframe (two months), and participant anonymity.

From the initial list of 60 potential participants, 49 individuals agreed to participate. From these individuals, 30 (ten from each category) were requested to complete the survey. If a chosen participant failed to respond within the specified timeframe, another participant from the same category was approached. This process continued until ten participants from each category completed the survey.

3.3.5 Step 5. Final Selection of Indicators and Calculation of their Weights

Final Selection of Indicators. The survey responses were downloaded into an MS Excel spreadsheet and were divided into two sections: a. preliminary list of indicators and b. additional indicators.

Preliminary List of Indicators. The responses related to the relevance of the preliminary list of indicators are presented in Table 3. All preliminary selected KPIs were considered relevant by more than 75% of the participants.

Table 3 Survey responses on the relevance of the preliminary list of KPIs.

HPI Code	KPI Code	KPI	Relevance Responses			
			No	%	Yes	%
E-1	E-1.1	Global warming	4	13%	26	87%
	E-1.2	Acidification	6	20%	24	80%
	E-1.3	Eutrophication	5	17%	25	83%
	E-1.4	Terrestrial ecotoxicity	2	7%	28	93%
	E-1.5	Freshwater ecotoxicity	2	7%	28	93%
	E-1.6	Marine ecotoxicity	2	7%	28	93%
E-2	E-2.1	Human toxicity	1	3%	29	97%
	E-2.2	Ozone layer depletion	4	13%	26	87%
E-3	E-3.1	Energy consumption	2	7%	28	93%
	E-3.2	Land use	1	3%	29	97%
	E-3.3	Water use	3	10%	27	90%
Ec-1	Ec-1.1	Investment	4	13%	26	87%
	Ec-1.2	Profit margin	0	0%	30	100%
	Ec-1.3	Carbon offset	2	7%	28	93%
	Ec-1.4	Production costs	4	13%	26	87%
S-1	S-1.1	Job creation & employment	2	7%	28	93%
S-2	S-2.1	Health & safety/Production	3	10%	27	90%
	S-2.2	Health & safety/Processing	1	3%	29	97%

Additional Indicators. Twenty-six participants suggested a total of 45 additional indicators. However, most of the participants did not suggest measurable indicators, instead, they provided a description. Therefore, the NVivo qualitative analysis software was used to code and categorise these descriptive responses into actual TBL indicators. Before uploading responses into NVivo, these were revised to address any orthographic errors and to maintain uniformity of the language. For example, 'CO_2' was renamed as 'carbon dioxide' across all responses.

Figure 4 presents the word cloud of the most frequent 50 words found in the responses. The five most prevalent words were carbon (17 occurrences), soil (16), sequestrated (8), health (6), and biodiversity (4).

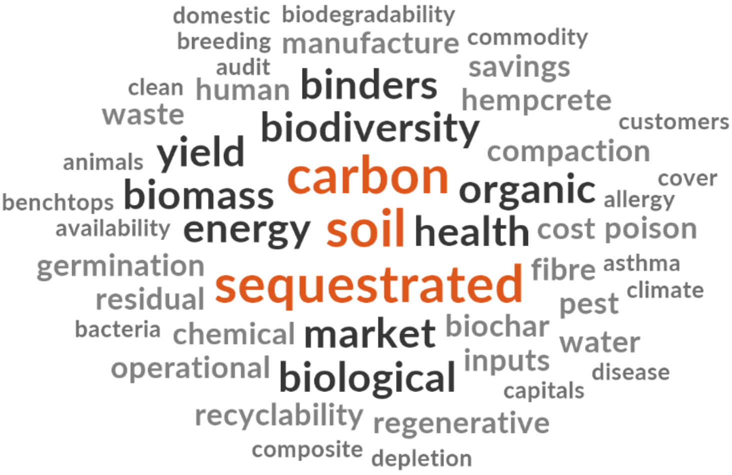


Figure 4 Word cloud for the most frequent 50 words found on open answers related to additional indicators.

Both deductive and inductive line-by-line coding methods were employed to code the 45 open responses using the NVivo software. From these, 22 answers were discarded due to the following reasons:

- Five answers were suggestions or comments instead of new indicators.
- Seven indicators overlapped with three preliminary KPIs i.e., global warming, energy consumption, and carbon offset.
- Seven answers suggested indicators beyond the scope of this research (e.g. markets, use and end-of-life).

The remaining 23 answers were categorised into nine new KPIs, which were further grouped into three HPIs as shown in Table 4.

Table 4 Additional HPIs and KPIs and the number of participants that suggested them.

Sustainability objective	Environmental				Social	
HPI	Soil health		Ecosystem		Happiness	
	Soil organic carbon	7	Biodiversity	4	Happiness	3
	Soil compaction	2				
	Soil rotation	2				
KPI	Soil remediation	2				
	Soil properties	2				
	Soil biodiversity	1				
	Soil practices	1				

The following criterion were used to finalise the selection of indicators [41]:

- The preliminary indicator was considered 'relevant' by more than 50% of respondents (≥15).
- The new indicator was proposed by more than 25% of participants (≥7).

As mentioned above, the preliminary list of indicators was considered relevant by more than 50% of the participants. Therefore, all primarily selected indicators were included in the final list. In the case of additional indicators, only soil organic carbon was suggested by more than 25% of respondents. Consequently, it was included in the final list of KPIs under the HPI soil health and the environmental objective of sustainability (E). A brief description of these indicators is as follows:

> E-4: Soil Health. Soil health encompasses the ecological balance and soil functionality, reflecting its ability to support a diverse and productive ecosystem [84]. As an indicator, it requires evaluating physical, chemical, and biological properties to determine their response to soil use and management [85].
>
> *E-4.1. Soil Organic Carbon*. This property is recognised as the most important indicator of soil health because it presents the availability of soil organic matter, vital for plant growth via nutrient cycling, water conservation, and by providing soil structural stability [86]. The unit of measurement for soil organic carbon is kg of CO_2eq per MPa of hemp-based building material.

In summary, 19 KPIs were selected to conduct a comprehensive LCSA for hemp-based materials in Australia. The distribution of TBL indicators is as follows:

- Environmental: global warming, acidification, eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity, ozone layer depletion, energy consumption, land use, water use, and soil organic carbon.
- Economic: investment, profit margin, carbon offset, and production costs.
- Social: job creation and employment, health and safety/production, and health and safety/processing.

The environmental, economic and social indicators were calculated using the ELCA, LCC and SLCA tools, respectively.

Calculation of Weights. The weights of each KPI, HPI and sustainability objective represented their significance in terms of sustainability performance of hemp-based materials. These weights were determined based on the survey responses in terms of the level of importance of the KPIs (Table 5). This assessment was conducted using a 4-point Likert-type scale where 1 = somewhat important, 2 = moderately important, 3 = important and 4 = very important.

Table 5 Survey responses on the importance of the final list of KPIs.

KPI Code	KPI	Importance			
		Somewhat Important	Moderately Important	Important	Very Important
E-1.1	Global warming	1	2	10	13
E-1.2	Acidification	4	3	9	8
E-1.3	Eutrophication	4	5	9	7
E-1.4	Terrestrial ecotoxicity	4	5	9	10
E-1.5	Freshwater ecotoxicity	4	5	9	10
E-1.6	Marine ecotoxicity	4	5	9	10
E-2.1	Human toxicity	6	4	7	12
E-2.2	Ozone layer depletion	7	5	9	5
E-3.1	Energy consumption	3	5	7	13
E-3.2	Land use	2	6	11	10
E-3.3	Water use	2	1	8	16
E-4.1	Soil organic carbon	0	0	3	4
Ec-1.1	Investment	0	2	13	11
Ec-1.2	Profit margin	1	3	11	15
Ec-1.3	Carbon offset	1	5	5	17
Ec-1.4	Production costs	0	6	7	13
S-1.1	Job creation & employment	1	4	10	13
S-2.1	Health & safety/Production	1	2	11	13
S-2.2	Health & safety/Processing	1	4	7	17

The total point value of each impact category was calculated using Equation (2).

$$W_k = n_{k1} * 1 + n_{k2} * 2 + +n_{k3} * 3 + n_{k4} * 4 \tag{2}$$

where:
W_k = total point value of the KPI *k,*
k = KPI "*k*",
n_{k1} = number of 'somewhat important' responses for KPI *k,*
n_{k2} = number of 'moderately important' responses for KPI *k,*
n_{k3} = number of 'important' responses for KPI *k,*
n_{k4} = number of 'very important' responses for KPI *k.*

The total weight for the total number of KPIs has been calculated using Equation (3).

$$W_{total} = \sum_{i=1}^{19} W_k \tag{3}$$

where:
W_{total} = total weight for the 19 KPIs,
k = 1, 2, 3, …, 19 KPIs.

The weight for each KPI was calculated using Equation (4).

$$W'_k = \frac{W_k}{W_{total}} \tag{4}$$

where:
W'_k = weight for KPI *k.*

The weights of KPIs under each HPI were added to calculate the weight of the respective HPI. Likewise, the weights of HPIs were used to calculate the respective sustainability objectives. Table 6 presents the weights for the 19 KPIs, seven HPIs and the three TBL objectives.

Table 6 Weights of the final list of 19 KPIs, HPIs and the TBL objectives.

KPI		KPI weight	HPI		HPI weight	TBL		TBL weight
E-1.1	Global warming	0.0561	E-1	Ecosystem	0.3019	E	Environmental	0.5839
E-1.2	Acidification	0.0445						
E-1.3	Eutrophication	0.0445						
E-1.4	Terrestrial ecotoxicity	0.0523						
E-1.5	Freshwater ecotoxicity	0.0523						
E-1.6	Marine ecotoxicity	0.0523						
E-2.1	Human toxicity	0.0535	E-2	Human health	0.0948			
E-2.2	Ozone layer depletion	0.0413						
E-3.1	Energy consumption	0.0555	E-3	Resources	0.1710			
E-3.2	Land use	0.0561						
E-3.3	Water use	0.0594						
E-4.1	Soil carbon	0.0161	E-4	Soil health	0.0161			
Ec-1.1	Investment	0.0561	Ec-1	Producer perspective	0.2361	Ec	Economic	0.2361
Ec-1.2	Profit margin	0.0645						
Ec-1.3	Carbon offset	0.0606						
Ec-1.4	Production costs	0.0548						
S-1.1	Job creation & employment	0.0587	S-1	Community	0.0587	S	Social	0.1800
S-2.1	Health & safety/Production	0.0581	S-2	Workers	0.1213			
S-2.2	Health & safety/Processing	0.0632						
Total		1.0000			1.0000			1.0000

3.4 Life Cycle Interpretation

There are a range of ways for interpreting LCSA outcomes [2]. In most cases ELCA, LCC, and SLCA results can be suitably presented through the use of graphs [87]. Commonly employed graphics in LCSA studies include radar charts, sustainability score dashboards, sustainability crowns, and sustainability triangles. Among these graphs, radar charts are particularly effective in displaying the performance of each TBL KPI without aggregation [88]. Moreover, the integration of threshold values and ELCA, LCC and SLCA results (expressed in KPI values) in radar charts can facilitate the identification of KPIs requiring improvement, also known as hotspots [25].

In the context of LCSA, the threshold value represents the best achievable performance whereas the minimum value is the worst performance for a specific KPI [24]. For instance, if the threshold value and minimum value for global warming (E-1.1) in the production of hemp-based boards in Australia are 0.001 kg CO_2eq/MPa and 0.032 kg CO_2eq/MPa and, respectively, any measured KPI value within this range indicates acceptable performance. The difference between the threshold value and the measured KPI value represents the gap to achieve the ideal target for that KPI, higher gaps indicate hotspots [24]. In the case of global warming, lower measured values signify better performance. Conversely, for other KPIs such as investment (Ec-1.1), profit margin (Ec-1.2), carbon offset (Ec-1.3), and job creation and employment (S-1.1), higher values represent better performance.

The life cycle interpretation stage of the LCSA framework of hemp-based boards was based on sustainability gap analysis and its visualisation in radar charts. This can aid in decision-making processes for identifying the hotspots throughout the life cycle of the product and finding mitigation strategies to improve its sustainability performance.

3.4.1 Determination of Minimum and Threshold Values

The selection of minimum and threshold values for the 19 TBL KPIs was primarily based on the sustainability data from existing studies on hemp-based building materials in Australia. Additional surrogate data were sourced from sustainability reports by governmental bodies such as Safe Work Australia, as well as environmental product declarations (EPDs), financial, and annual reports from manufacturers of similar non-structural boards in Australia, particularly wood-based panels and gypsum plasterboards [89]. Table 7 presents the minimum and threshold values assigned to each KPI.

Table 7 Minimum and threshold values for KPIs of non-structural hemp-based boards in Australia.

KPI		Unit	Minimum value	Threshold value
E-1.1	Global warming	kg CO_2eq/MPa	3.19E-02	1.03E-03
E-1.2	Acidification	kg SO_2eq/MPa	2.85E-04	2.60E-05
E-1.3	Eutrophication	kg PO_4eq/MPa	1.87E-04	1.57E-05
E-1.4	Terrestrial ecotoxicity	kg 1,4-DB eq/MPa	3.77E-04	3.17E-05
E-1.5	Freshwater ecotoxicity	kg 1,4-DB eq/MPa	6.92E-03	8.70E-04
E-1.6	Marine ecotoxicity	kg 1,4-DB eq/MPa	8.88E+00	5.09E+00
E-2.1	Human toxicity	kg 1,4-DB eq/MPa	5.75E-03	4.99E-05

E-2.2	Ozone layer depletion	kg CFC-11 eq/MPa	2.37E-08	1.97E-10
E-3.1	Energy consumption	MJ/MPa	1.48E-07	9.00E-08
E-3.2	Land use	ha per annum/MPa	6.24E-08	3.14E-10
E-3.3	Water use	m^3 H_2O/MPa	2.17E-03	6.59E-09
E-4.1	Soil organic carbon	kg CO_2eq/MPa	8.37E-04	1.16E-06
Ec-1.1	Investment	AUD/MPa	0	4.80E-04
Ec-1.2	Profit margin	%	10	17.5
Ec-1.3	Carbon offset	AUD/MPa	4.00E-04	7.00E-04
Ec-1.4	Production cost	AUD/MPa	8.42E-02	7.79E-02
S-1.1	Job creation & employment	FTE per annum	7.4	8.6
S-2.1	Health & safety/Production	Serious claim/employee	2.02E-02	1.79E-02
S-2.2	Health & safety/Processing	Serious claim/employee	1.81E-02	1.56E-02

Environmental Minimum and Threshold Values. An increasing number of EPDs for building materials, including non-structural boards, are being published in Australia. Many of these EPDs were available online through EPD Australasia, which provides independently verified EPDs for businesses in Australia and New Zealand [90]. The EPDs for non-structural boards available [91, 92] were reviewed to obtain a range of environmental KPI values, with the worst and best values for each KPI assigned as the minimum and threshold value, respectively.

Economic Minimum and Threshold Values.

Ec-1.1. Investment. The largest manufacturers of non-structural boards in Australia are CSR, Knauf Gypsum, and Etex Australia Pty Limited, with market shares of 32.1%, 25.8%, and 24.6%, respectively [93]. The investment from these companies have ranged between 0 to 32 million AUD per year during the last five years [94-96]. Considering that Australia produces around one million tonnes of non-structural boards annually [97] which is equivalent to approximately 65 billion of MPa of bending strength [18], the minimum and threshold value were set at 0 and 0.00048 AUD/MPa of hemp-based material, respectively.

Ec-1.2. Profit Margin. The annual profit margin of the board industry in Australia has ranged from 10% to 17.5% over the past five years [93]. These figures were used as the minimum and threshold value, respectively.

Ec-1.3. Carbon Offset. In Australia, the carbon emissions from the production of non-structural boards are around 0.00862 kg CO_2eq/MPa [90], whereas the carbon emissions of hemp-based boards can range from - 4.53E-03 kg CO_2eq/MPa to - 1.20E-02 kg CO_2eq/MPa [18]. Therefore, the potential reduction in CO_2eq emissions by replacing traditional boards with hemp-based boards can vary from 0.0132 kg CO_2eq/MPa to 0.0206 kg CO_2eq/MPa. Considering that the current price of one ACCU fluctuates between 30.5 and 32.0 AUD [98], the minimum value has been established as 0.0004 AUD/MPa and the threshold value as 0.0007 AUD/MPa.

Ec-1.4. Production Cost. The production cost of the volume required to achieve a bending strength of 1 MPa of hemp-based board can fluctuate between 0.0779 and 0.0842 AUD in Australia [18]. Therefore, these figures were used as the threshold value and minimum value respectively.

Social Minimum and Threshold Values.

S-1.1. Job Creation and Employment. The average number of full-time employees (FTE) per enterprise in the board industry in Australia has ranged between 7.4 and 8.6 over the past five years [93]. These figures were used as the minimum and threshold value, respectively.

S-2.1. Health and Safety/Production. In Australia, the incidence rate have ranged from 17.9 to 20.2 serious claims per thousand employees over the last five years in the agricultural sector [78], equating to 0.0179 and 0.0202 serious claims per employee. These incidence rates were used as the threshold value and minimum value, respectively, for the health and safety indicator at the production of hemp.

S-2.1. Health and Safety/Processing. The incidence rate in the manufacturing sector in Australia have ranged from 15.6 to 18.1 serious claims per thousand employees over the last five years [78], equating to 0.0156 and 0.018 serious claims per employee. These incidence rates were used as the threshold value and minimum value, respectively.

3.4.2 Calculation of Sustainability Performance Gaps

Gaps of KPIs. The gap for a specific KPI was defined as the difference between the threshold value and the measured value of the KPI [24]. Larger gaps indicated hotspots meaning that the implementation of sustainability strategies is required to reach the threshold value. The gap for each KPI is calculated using Equation (5).

$$Gap_k = tv_k - hb_k \tag{5}$$

where:
k = KPI "k",
Gap_k = gap of k,
tv_k = threshold value of k,
hb_k = hemp-based board value of k.

To present ELCA, LCC and SLCA results in a radar chart and identify hotspots, KPI gaps were converted into a 5-point Likert scale using Equation (6). On this scale, 0 indicated the minimum value, and 5 represented the threshold value or best sustainability performance [24]. Gap values below -2.5 highlighted hotspots needing urgent improvement to achieve desired sustainability levels (i.e., 5).

$$Gap_k = \left| \frac{min_k - hb_k}{\left(\frac{tv_k - hb_k}{5}\right)} \right| - 5 \tag{6}$$

where:
Gap_k = gap of k expressed into a 5-point Likert scale,
min_k = minimum value of k.

Performance Gaps of KPIs. Equation (7) is applied to calculate the performance gap of a specific KPI [24].

$$WGap_k = Gap_k * W'_k \tag{7}$$

where:
$WGap_k$ = weighted or performance gap of *k,*
W'_k = weight of *k.*

Performance Gaps of HPIs. According to the hierarchical structure of the LCSA framework, the performance gap of each HPI is the average value of the performance gaps of the corresponding KPIs (Equation 8).

$$Gap_h = \frac{\sum_{i=1}^{H} WGap_{k-h}}{W_h'} \tag{8}$$

where:
h = *HPI "h",*
H = 1, 2, 3, …, H KPIs under HPI *h*,
Gap_h = performance gap of *h,*
$WGap_{k-h}$ = performance gap of KPI *"k"* under HPI *h,*
W'_h = weight of *h.*

Performance Gaps of TBL Objectives. The performance of each sustainability objective i.e., environmental, economic and social, is the average value of the performance gaps of the HPIs under the corresponding objective (Equation 9).

$$Gap_t = \frac{\sum_{i=1}^{T} Gap_{h-t}}{T} \tag{9}$$

where:
t = sustainability objective *"t",*
T = 1, 2, 3, …, T HPIs under sustainability objective *t*,
Gap_t = performance gap of *t,*
Gap_{h-t} = performance gap of HPI *"h"* under sustainability objective *t.*

Sustainability Score. The sustainability score of the product system is the average value of the gaps of the sustainability objectives (Equation 10). A score lower than - 2.5 indicates that the product requires significant improvement to achieve the ideal sustainability target [24]. In such cases, a comprehensive gap analysis of the entire hierarchical structure is necessary to identify which objectives, HPIs, and KPIs need enhancement.

$$SC = \frac{Gap_E + Gap_{Ec} + Gap_S}{3} \tag{10}$$

where:
SC = sustainability score*,*
Gap_E = performance gap for the environmental performance,
Gap_{Ec} = performance gap for the economic performance,
Gap_S = performance gap for the social performance.

4. Test of the Life Cycle Sustainability Assessment Framework for Hemp-Based Boards

To test the applicability of the LCSA model, both real and hypothetical data were used in the ELCA, LCC, SLCA conducted to calculate the environmental, economic, and social KPIs. Some environmental and economic KPIs values were sourced from Rivas Aybar, John [18], which used the ELCA tool to estimate KPIs of hemp-based boards. Hypothetical values were used for the economic and social KPIs applying the LCC and SLCA, respectively.

4.1 Life Cycle Interpretation

The performance gaps for KPIs, HPIs, TBL objectives, and the sustainability score, were measured on a 5-point Likert Scale (Table 8). These values were calculated following the procedure explained in section 3.4.2, using Equations (5) to (10).

Table 8 The Performance gaps for each KPI, HPI, TBL objectives and the sustainability score expressed in a 5-point Likert scale.

KPI		Gap KPI	Performance Gap KPI	HPI		Performance Gap HPI	TBL Objective		Performance Gap TBL Objective	Sustainability Score
E-1.1	Global warming	0.00	0.00	E-1	Ecosystem	-2.22	E	Environmental	-2.25	-1.83
E-1.2	Acidification	-1.61	-0.08							
E-1.3	Eutrophication	-2.35	-0.12							
E-1.4	Terrestrial ecotoxicity	-1.92	-0.12							
E-1.5	Freshwater ecotoxicity	-1.10	-0.07							
E-1.6	Marine ecotoxicity	-4.77	-0.29							
E-2.1	Human toxicity	-4.33	-0.25	E-2	Human Health	-3.60				
E-2.2	Ozone layer depletion	-1.76	-0.09							
E-3.1	Energy consumption	-1.64	-0.11	E-3	Resources	-2.80				
E-3.2	Land use	-4.19	-0.26							
E-3.3	Water use	-1.65	-0.11							
E-4.1	Soil organic carbon	-0.23	-0.01	E-4	Soil Health	-0.39				
Ec-1.1	Investment	-4.85	-0.23	Ec-1	Producer Perspective	-2.38	Ec	Economic	-2.38	
Ec-1.2	Profit margin	-3.81	-0.18							
Ec-1.3	Carbon offset	-1.80	-0.12							
Ec-1.4	Production costs	-3.46	-0.02							
S-1.1	Job creation & employment	-1.64	-0.06	S-1	Community	-1.10	S	Social	-0.86	
S-2.1	Health & Safety/Production	-0.95	-0.06	S-2	Workers	-0.63				
S-2.2	Health & Safety/Processing	-0.38	-0.02							

4.1.1 Sustainability Score and Performance Gaps of TBL Objectives

The sustainability score for the production of hemp-based boards in Australia has been estimated to be -1.83. This score indicates that the product is 1.83 points less than the maximum value on the Likert scale (Figure 5). The analysis reveals that the economic objective, with a performance gap of -2.38, needs the most attention to improve the sustainability performance (Table 8). The environmental objective follows with a performance gap of -2.25. Among the three sustainability dimensions, the social perspective with a gap of -0.86 requires less immediate attention compared to the economic and environmental dimensions.

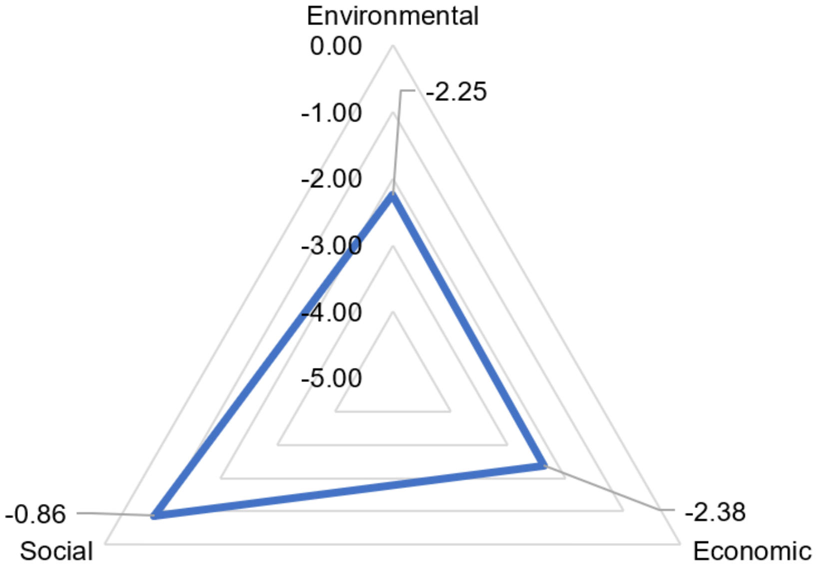
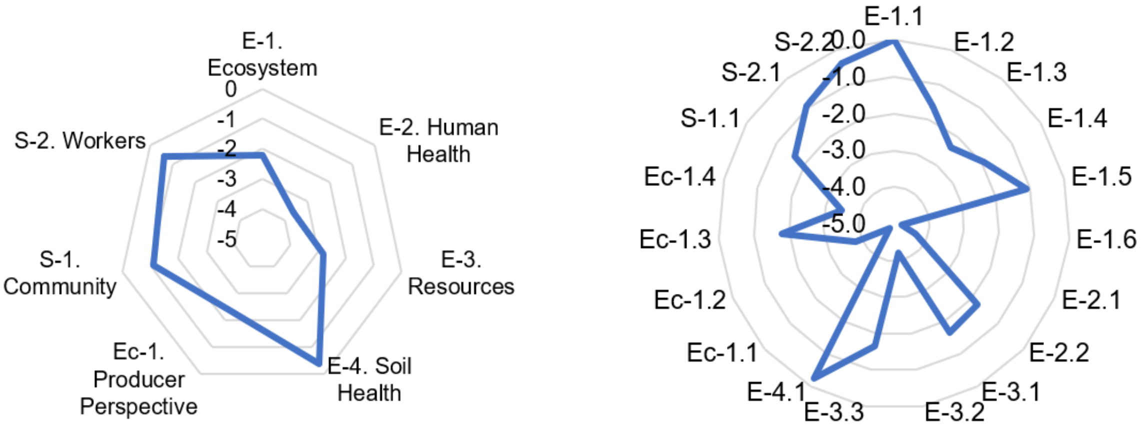


Figure 5 Performance gaps of environmental, social and economic objectives.

4.1.2 Performance Gaps of HPIs and KPIs

The reason the economic and environmental objectives exhibited the higher performance gaps is that the HPIs of human health (E-2), resources (E-3), and producer perspective (Ec-1) have the largest gaps of -3.60, -2.80 and -2.38, respectively (Figure 6a). Under these HPIs, the largest gaps were found in the KPIs investment (Ec-1.1), marine ecotoxicity (E-1.6) and human toxicity (E-2.1) (Figure 6b). The poor sustainability performance in these KPIs can be attributed to several factors.



(a)

(b)

Figure 6 (a). Performance gap of each HPI and Figure 5(b). Performance gap of each KPI (E-1.1 Global warming; E-1.2 Acidification; E-1.3 Eutrophication; E-1.4 Terrestrial ecotoxicity; E-1.5 Freshwater ecotoxicity; E-1.6 Marine ecotoxicity; E-2.1 Human toxicity; E-2.2 Ozone layer depletion; E-3.1 Energy consumption; E-3.2 Land use; E-3.3 Water use; E-4.1 Soil organic carbon; Ec-1.1 Investment; Ec-1.2 Profit margin; Ec-1.3 Carbon offset; Ec-1.4 Production costs; S-1.1 Job creation & employment; S-2.1 Health & Safety/Production; and, S-2.2 Health & Safety/Processing).

For instance, producing and processing hemp-based materials require substantial investment for specific agricultural machinery, processing, and manufacturing facilities [12, 99]. It could be also because of the fact that hemp growers might face challenges in making hemp economically competitive compared to other crops [70]. Similarly, the firms aiming to maximise profits by using hemp to produce building products must ensure that the hemp remains cost-competitive against other materials, such as minerals or wood-based products. These factors can adversely affect the KPIs investment and must be addressed to achieve desired sustainability outcomes.

On the environmental dimension, the challenges associated with hemp-based products primarily arise from the pre-farm and on-farm stages [100]. The use of fertilisers, herbicides, and potentially pesticides increases the marine and human toxicity impact resulting on a higher gap for these KPIs [9, 101]. Therefore, environmentally friendly alternatives to conventional agricultural inputs must be considered and assessed to ensure that environmental improvements do not compromise economic or social performance.

5. Implications and Limitations of the Life Cycle Sustainability Assessment Framework

The proposed LCSA framework for assessing the sustainability performance of hemp-based boards in Australia was tested using a set of real and hypothetical data. The data was used to ELCA, LCC and SLCA to calculate environmental, economic and social KPIs previously selected for a mechanical strength of 1 MPa of hemp-based material and a system boundary from 'cradle to gate'. The participatory approach used to select, validate and weight TBL KPIs aimed to determine product and region-specific indicators.

The use of gap analysis and radar charts facilitated the interpretation of ELCA, LCC and SLCA results, enabling the determination of the overall sustainability score and the identification of hotspots. Moreover, the use of radar charts provided a user-friendly visualisation tool that can be directly applied by both general public and LCSA practitioners, allowing them to easily identify individual HPIs or KPIs requiring improvement to enhance the overall sustainability performance of the product system.

Nevertheless, it is important to recognise the fact that the system boundary of this LCSA was limited to the production stage which consisted of pre-farm, on-farm, and post-farm phases. Hemp-based materials are novel in Australia, hence, the information on the use and end-of-life phases, as well as the perspectives of retailers and end-users, is scarce. There is limited data regarding the environmental, economic, and social aspects of hemp production and hemp-based materials production [11]. To address this data gap, surrogate information from more established traditional construction materials with similar technical performance was used. Therefore, it is recommended that as the availability of sustainability data of hemp-based materials in Australia increases, future studies could gradually consider other life cycle stages. Similarly, the threshold values should be updated with new data.

6. Conclusions

The research introduces a novel LCSA framework for assessing the production of hemp-based building materials in Australia. The significance of this research lies in its novel approach for assessing hemp-based composites through a holistic sustainability lens. Unlike previous studies that have primarily focused on individual aspects such as environmental impacts, this research integrates all three dimensions of sustainability, environmental, economic, and social into one sustainability score for a comparative assessment to facilitate the decision-making process and to provide a comprehensive framework for evaluating the broader implications of these novel materials in the construction sector.

The LCSA framework was based on the following formulation: LCSA = ELCA + LCC + SLCA and consisted of four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation. The functional unit was based on the technical performance of the hemp-based building material, which was the mechanical strength of 1 MPa. The system boundary included all production stages: pre-farm, on-farm, and post-farm. The methodology involved a literature review and a participatory approach to select and weight region- and product-specific environmental, economic, and social KPIs estimated by using ELCA, LCC and SLCA, respectively. The participatory approach consisted of an online-based survey to gather the perspectives of 30 participants representing three major stakeholder categories: construction industry, hemp industry, and government and academia, in Australia. All preliminary selected KPIs were considered relevant by more than 75% of the participants. Ten participants from each stakeholder category selected and weighted 19 sustainability KPIs consisting of 12 environmental KPIs, four economic KPIs, and three social KPIs which were categorised under seven HPIs under the three sustainability objectives. This participatory approach ensured that the selected sustainability indicators were both regionally relevant and industry specific.

For the interpretation and visualisation of the ELCA, LCC and SLCA results and to identify the KPIs and HPIs representing hotspots, the framework used radar charts and gap analysis. Finally, the applicability of the LCSA was tested using a set of real and hypothetical data for assessing and comparing sustainability performance of hemp-based boards. The test of the framework demonstrated its effectiveness in presenting LCSA outcomes and identifying hotspots. The framework provided a tool for communicating LCSA results to the relevant stakeholders and LCSA practitioners, assisting them in the decision-making processes for improving the sustainability outcomes of the production of hemp-based low-carbon materials.

Future research should include other life cycle stages, such as use and end-of-life, and incorporating market and user perspectives to the comprehensive environmental, economic and social conclusions on hemp-based materials in Australia.

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Author Contributions

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Competing Interests

The authors have declared that no competing interests exist.

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