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Review

Application of Recycled Cardboard to Construction Based on Life Cycle Assessment

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Abstract: Typical household recyclable bin in Australia contains around 60% of waste cardboard. Given the possibilities of developing a construction material, this study conducted a life cycle assessment (LCA) comparing the development of cardboard trusses with © timber trusses, encompassing production to construction. The results show that cardboard trusses offer significant environmental benefits, including a 73% reduction in climate change category, an 83% decrease in ozone-depleting potential, and almost complete avoidance of agricultural land occupation compared to timber trusses, showcasing their sustainability. In both material manufacturing and material transportation, cardboard trusses prioritize climate change mitigation, accounting for over half of the environmental impact. Timber trusses, in contrast, heavily impact land occupation and exhibit climate change dominance. A benefit analysis highlights advantages of cardboard trusses, particularly in reducing land occupation, sustainability, circular economy, and particulate matter formation. The life cycle cost analysis demonstrates an impressive 83% cost reduction for cardboard trusses compared to timber trusses, despite higher labor costs during manufacturing.

Keywords: cardboard; recycle; timber; life cycle analysis; truss; construction

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1. Introduction

Typical household recyclable bin in Australia contains around 60% of waste cardboard [1]. A report from the United Nations [2] suggests that a global effort is needed to mitigate the ecological effects stemming from human actions. Within this framework, the construction and building sector is pivotal in diminishing greenhouse gas emissions (GHGs) and in fulfilling goals related to energy consumption reduction. As the global population grows, the consumption of natural resources increases, while landfills overflow with discarded materials. Collaborations between industrial sectors and academic researchers are emerging to devise sustainable waste management solutions. Innovations in recycling and repurposing waste aim to minimize reliance on landfills and promote a circular economy by ensuring that products and materials maintain their value [3]. During the fiscal interval spanning 2018 to 2019, Australia reported the generation of 74 million tonnes of waste. This figure signifies a 10% augmentation relative to the data recorded for the biennium 2016–2017 [4]. Australia is promoting sustainable development in the waste recycling sector to increase the recycling rate. One of the priority wastes in Australia is paper/cardboard waste [4]. Estimations suggest an average consumption of 235 kg of paper and cardboard per individual in Australia [4,5]. Reports indicate that, in the fiscal period of 2018–2019, the country generated 5.92 million tonnes of waste from these materials, of which 1.9 million tonnes were disposed of in landfills [5,6]. Due to an export ban on waste, significantly increased amounts of paper and cardboard waste are expected to accumulate in the landfill system. In this millennium, the emphasis on sustainability is intensifying [7], highlighting the necessity for resource conservation and the development of innovative recycling methods to maintain ecological balance [8]. This push toward sustainability has catalyzed a burgeoning research field focused on green material technologies. Through various waste streams, scholars across multiple institutions are investigating ways to mitigate environmental degradation and implement recycling within the construction sector [9–12]. In this drive toward sustainability, the construction industry is the largest sector in the world in terms of asset management [8]. Researchers have established novel methods to recycle different types of waste materials into construction materials. A potential resource/application worth exploring is the utilization of cardboard waste as a replacement for one of the widely used construction materials, 'timber'. Cardboard waste, when repurposed as a substitute for timber, is recognized globally for its environmentally friendly, biodegradable, and recyclable qualities, making it more accessible than many other waste materials.

Recent research on timber and cardboard trusses has focused on sustainable and innovative construction methods. Hybrid timber-cardboard sandwich beams have shown promising results, offering equivalent performance to recycled cores while utilizing up to 91% of waste materials by volume [13]. Cardboard's potential as a construction material has been explored, with studies indicating its viability as a timber replacement despite challenges like water absorption and fire resistance [14]. Glued timber trusses have emerged as a commercial alternative to traditional steel-fastened trusses, offering benefits such as top chord support without hangers and cost-effectiveness for large spans [15,16]. Additionally, all-wood trusses using plywood nodes and wooden pegs have been developed to optimize resource efficiency and minimize environmental impact. These designs incorporate parametric optimization and wood–wood connections to reduce material consumption and eliminate the need for steel components [17].

In the past ten years, the evaluation of environmental impacts associated with construction materials has garnered increased attention [18–20]. Employing a life cycle assessment (LCA), a method endorsed by ISO 14040 [21], allows for the environmental scrutiny of innovative materials derived from waste. Through a LCA, it is possible to analyze the flow of materials and energy, assessing the ecological footprint and lifecycle impact of products and processes. This approach is recognized for its ability to both qualitatively and quantitatively determine the environmental effects and advantages associated with a procedure [20].

This research explores the environmental and economic implications from the cradle to the gate of a truss made from recycled cardboard by employing an innovative method, in contrast to a traditional timber truss of comparable efficiency. This study adheres to the ReCiPe midpoint (Europe H) methodology for assessing impacts. The findings will provide insight into viable, eco-friendly substitutes for timber using cardboard waste in both the manufacturing and construction sectors.

This research conducted a comprehensive LCA to analyze the environmental footprint of trusses made from recycled cardboard, from raw material extraction and processing to transportation and final truss fabrication. The innovative use of recycled cardboard in truss production is highlighted as a pioneering approach. To date, no studies have been published that evaluate and compare the LCA, including a benefits analysis of trusses from recycled cardboard using a performance indicator methodology. This study's quantification of the environmental effects from the 'cradle to gate' stages of recycled cardboard trusses, and their environmental comparison with traditional timber trusses, facilitated the identification of both the environmental impacts and the potential for enhancing environmental outcomes. The results are intended to inform future policy development aimed at reducing emissions and environmental impacts within the construction sector.

2. Methodology

2.1. Goal and Scope Definition

This investigation aimed to conduct an in-depth LCA to explore both the environmental impacts and advantages of producing cardboard trusses in Australia, juxtaposing these findings against the environmental footprint of traditional timber trusses. Such trusses are deemed appropriate for structural uses within Australian residential buildings.

The aims of this investigation were the following: (1) the environmental impacts produced by waste cardboard trusses are to be assessed and juxtaposed with those from standard timber trusses; (2) the main contributors to environmental impacts are to be defined, and enhancements during the 'cradle to gate' life cycle are to be pinpointed; (3) an elucidation of the cost–benefit analysis for employing waste cardboard in the fabrication of trusses is to be offered; and (4) environmental impacts are to systematically categorized with real-world data, following the ISO 14040 standard, using the ReCiPe midpoint (H) 2016 environmental impact assessment method, focusing on key categories such as climate change, to translate these impacts into actionable insights.

For the LCA analysis, methodologies encompassing performance indicators (quantified through a unit of functional performance) and a strength-based approach for LCA analysis were employed. For this analysis, a strength-based approach was chosen due to its ability to eliminate differentiation between material and structural scales [22]. It compares the conventional timber truss and cardboard truss under a comparable strength while maintaining similar conditions in shape, volume, and truss production methods. The tensile strength of both conventional timber and cardboard trusses was hypothesized to be similar for this study (i.e., 10 MPa), although the benefits will increase when considering higher tensile strengths (i.e., producing high strength cardboard trusses are more beneficial than corresponding timber elements). This method enables the adjustment of impacts for differing tensile strengths of the truss, allowing for both comparative and contributory analyses within the LCA framework.

This investigation was conducted from a cradle-to-gate viewpoint, covering the extraction and manufacturing of raw materials, material transportation, truss production, and waste management. According to ISO 14040 guidelines [21], the environmental impact analysis for both cardboard and timber trusses was carried out. The model construction, computations, and comparison of environmental impacts between the cardboard truss and the conventional timber truss, considering the 'cradle to gate' life cycle phases, were executed using SimaPro (version 8.2.0) LCA software.

An analysis of benefits was performed, taking into account the advantages of utilizing recycled cardboard instead of traditional timber. This quantification of benefits was carried out according to the impact categories recognized in the LCA impact assessment within SimaPro software, along with considerations of resource conservation, including the reduction in landfill use.

2.2. Functional Unit and System Boundary

For the LCA analysis, a fink truss configuration was selected. Figure 1 shows the truss structure. Its design flexibility renders it the preferred choice for roof construction. Characterized by its simple webbed structure, the fink roof truss offers an economical solution for roofing. This design effectively transfers roof loads to the wall plate. A span of 6 m, a slope of 15 degrees, and a volume of 0.323 m^3 were selected for the truss arrangement.

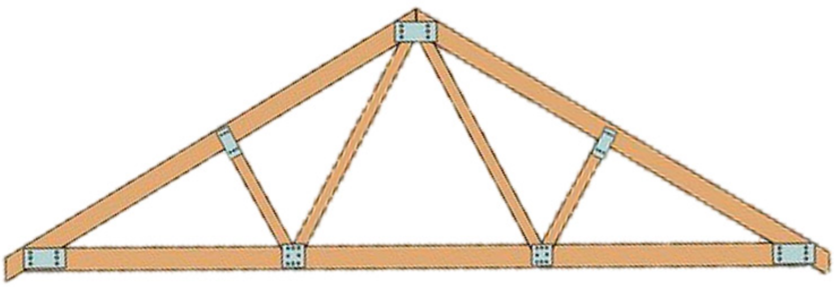

Figure 1. Fink truss configuration.

The selection of the functional unit for the process was based on the strength-oriented approach. Therefore, 'one unit of truss' serves as the functional unit for in-depth analysis in this research.

The system boundary of a study is an indicator of the limits of the system to be evaluated. The life cycle of the product has four key phases: material manufacture, material transportation, and truss manufacture. The life span of the truss is not considered for the trusses. The system boundary of this study is shown in Figure 2.

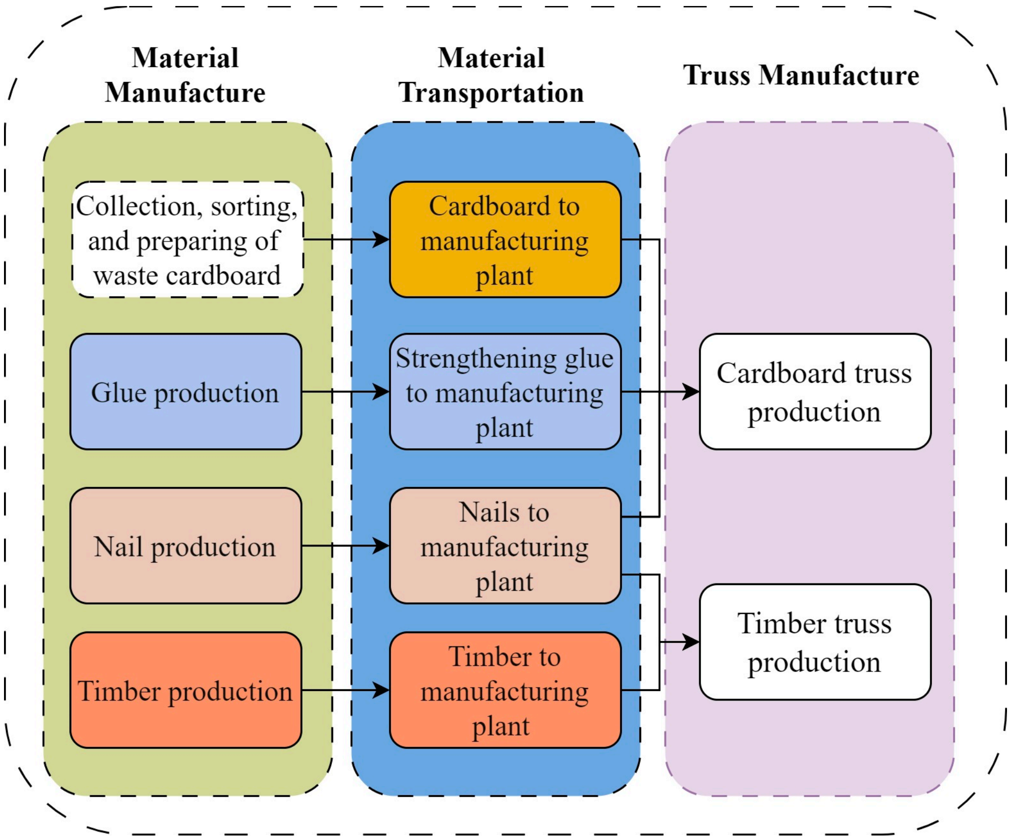

Figure 2. System boundary for truss life cycle.

In the material manufacture stage, glue, nail, and timber production are considered. Cardboard is regarded as waste material; thus, the process of cardboard collection, sorting, and preparation is not considered in the main comparison analysis. However, an uncertainty analysis was performed on various scenarios in which the waste cardboard collection, sorting, and preparation process represents 25%, 50%, 75%, and 100% of the equivalent processes in timber production. This analysis was motivated by real-world scenarios, where the collection, sorting, and preparation of cardboard waste demand resources and energy. Consequently, a sensitivity analysis was conducted to determine the extent to which the cardboard truss scenario can tolerate additional emissions while remaining environmentally advantageous compared to the timber truss scenario when accounting for the cardboard waste collection, sorting, and preparation process. In the material transportation stage, there are the processes of transporting cardboard to the manufacturing plant, strengthening glue to the manufacturing plant, nails to the manufacturing plant, and timber to the manufacturing plant are considered. In the truss manufacture stage, the processes of cardboard truss production and timber truss production are considered.

Table 1 shows lifecycle stages considered for each material and process. For the timber material, the material manufacture stage and material transportation stage are considered. For the cardboard material, since it is considered a waste material, material transport scenarios and the transportation stage are considered. For nails and other connecting materials, the material manufacture stage and material transportation stage are considered. For the glue, the material manufacture stage and material transportation stage are considered. Cardboard truss production and timber truss production only appear in the production stage. Our study assumes that all environmental impacts are attributed to the 'first life' of the cardboard as a packaging material. As a recycled product, the cardboard enters its 'second life' with a zero environmental burden, aligning with common LCA practices, where waste materials' impacts are not considered in their subsequent applications unless further treatment is required. This approach is supported by studies such as [23–25], which also exclude the environmental impacts of recycled materials' initial lifecycles from subsequent uses. In contrast, environmental burdens are accounted for when recycled materials undergo additional processing, as noted in [26]. In our case, since the recycled cardboard does not require further treatment before being used in truss construction, it is deemed to have zero environmental impact in its second life. This methodology is consistent with LCA standards that recognize recycled materials as entering new lifecycles without inheriting previous environmental burdens, provided that no additional transformations are involved.

Table 1. Life cycle phases for cardboard trusses, timber trusses, and their materials.

Material/Process	Timber	Cardboard	Nails and Other Connecting Materials	Strengthening Glue	Cardboard Truss	Timber Truss
Material Manufacture	√	-	√	√	-	-
Material Transportation	√	√	√	√	-	-
Truss Manufacture	-	-	-		√	√

3. Life Cycle Inventory Analysis

3.1. Material Manufacture

The recycled cardboard utilized in this study was sourced from Citywide Australia Pty Ltd., a specialized cardboard recycling company based in Footscray, VIC, Australia. This cardboard, regarded as a waste product, was repurposed specifically for the construction of cardboard trusses. Each truss was designed using 33 kg of cardboard. To enhance the structural integrity of these cardboard trusses, a specialized strengthening glue was required. The glue, procured from a supplier in Cheltenham, VIC, Australia, was used at a quantity of 64.5 mL per truss, adding a weight of 0.075 kg. It is important to note that in the case of cardboard trusses, the adhesive serves as the primary bonding agent, eliminating the need for nails entirely.

In contrast, the assembly of timber trusses follows a different process. The raw timber material, weighing 162 kg per truss, was sourced from companies that are locally available within the Melbourne region. Unlike the cardboard trusses, which rely on glue, timber trusses require nails for fastening the components together. These nails and other connecting materials were purchased from commercial hardware stores in Melbourne, Australia, with each truss incorporating 3 kg of nails. Timber trusses do not require any glue, relying solely on nails for their structural connections.

This distinction in the materials and fastening methods—where cardboard trusses necessitate glue but not nails, while timber trusses rely on nails without the use of glue—highlights the differences in construction techniques. The weights of materials were inputted into the SimaPro software for environmental assessment. The material quantities of the trusses are presented in the Table 2 inventory list.

Table 2. Inventory list.

Material	Source	Weight (kg)	Transportation Distance (km)
Recycled Cardboard (Per Truss)	Citywide Australia Pty Ltd., Footscray, VIC, Australia	33	22.5
Strengthening Glue (Per Truss)	Company in Cheltenham, VIC, Australia	0.075	29.8
Nails (Per Truss)	Commercial stores in Melbourne, Australia	3	16.7
Timber (Per Timber Truss)	Local companies in Melbourne, Australia	162	50

3.2. Material Transportation

The ranges of distances for every truss variant are aggregated in the Table 2 inventory list. Truss fabrication was projected to be situated in Melbourne, Australia. Diesel-powered heavy trucks, chosen for all logistical activities of raw materials served as the primary means of road transport. The calculation of the material transportation distances utilized authentic data. The product transportation distance and the material weight were used as input for the SimaPro software.

3.3. Truss Manufacture

In this study, we fabricated cardboard trusses on a laboratory scale, employing manual labor throughout the entire production process. Notably, the industrial-scale production of both cardboard and timber trusses followed an analogous manufacturing procedure. Consequently, when comparing the truss manufacturing stage, the energy and resource consumption effectively canceled each other out. Consequently, we assumed zero energy consumption for both cardboard and timber trusses. However, it is important to note that this study included labor costs in the overall cost analysis.

4. Impact Assessment Method and Impact Categories

The ReCiPe midpoint (Europe H) methodology was utilized in the life cycle impact assessment. This approach converts emission values into specific midpoint impact category indicators. In this method, environmental significance is often determined through qualitative associations, supported by statistical data and literature reviews [27]. For this analysis, twelve impact categories were assessed: climate change (kg CO_2 eq), ozone depletion (kg CFC11 eq), particulate matter formation (kg $PM_{2.5}$ eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), freshwater ecotoxicity (kg 1,4-DCB eq), marine ecotoxicity (kg 1,4-DBC eq), human toxicity (carcinogenic and non-carcinogenic) (kg 1,4-DBC eq), land use (m^2a crop eq), mineral resource scarcity (kg Cu eq), fossil resource scarcity (kg oil eq), and water consumption (m^3). Inventory data for each life cycle stage, including raw material production, transportation, and energy/electricity use, were obtained from the Ecoinvent 3.0 database using the SimaPro LCA software.

5. Results

5.1. Comparing the Environmental Impact of Cardboard Truss and Timber Truss

An analysis comparing the environmental impacts of cardboard and conventional timber trusses was conducted using the twelve categories specified by the ReCiPe midpoint methodology. The intensities of the characterized impacts for these categories are detailed in Appendix A. The variations in percentage between the two types of trusses across all midpoint categories are depicted in Figure 3.

When comparing the environmental impacts of cardboard trusses to those of timber trusses, several striking differences emerge. Cardboard trusses demonstrate a substantial reduction in climate change impact, emitting 73% less CO_2 equivalent (8.29 kg CO_2 eq) compared to timber trusses (30.7 kg CO_2 eq). This significant decrease underscores the potential of cardboard trusses to contribute more positively to climate change mitigation efforts.

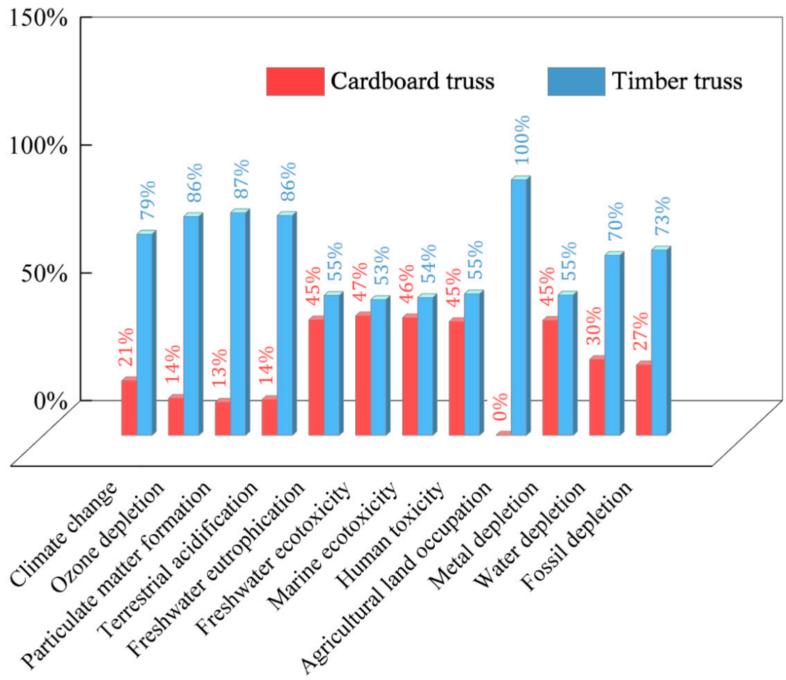

Figure 3. Midpoint characterization values of comparative percentages for cardboard and timber trusses (units: climate change (kg CO_2 eq), ozone depletion (kg CFC-11 eq), particulate matter formation (kg $PM_{2.5}$ eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), freshwater ecotoxicity (kg 1,4-DB eq), marine ecotoxicity (kg 1,4-DB eq), human toxicity (kg 1,4-DB eq), agricultural land occupation (m^2a crop eq), metal depletion (kg Fe eq), water depletion (m^3), fossil depletion (kg oil eq)).

Another critical area of difference lies in ozone depletion. Cardboard trusses exhibit an 83% lower ozone-depleting potential (2.72×10^{-7} kg CFC-11 eq) than timber trusses (1.62×10^{-6} kg CFC-11 eq), making them a far more environmentally sound choice in terms of protecting the ozone layer.

Particulate matter formation is another category where cardboard trusses outperform their timber counterparts. They generate 85% less particulate matter (1.45×10^{-2} kg $PM_{2.5}$ eq) compared to timber trusses (9.81×10^{-2} kg $PM_{2.5}$ eq), which can significantly benefit air quality and human health.

One of the most striking differences is in agricultural land occupation. Cardboard trusses require nearly 99.98% less land (3.59×10^{-1} m^2a crop eq) than timber trusses (1.55×10^3 m^2a crop eq), highlighting their potential to greatly reduce the land footprint associated with construction. However, it is important to note that while reduced land occupation is a benefit in terms of resource efficiency, it does not account for the ecological benefits provided by forests, such as soil conservation, water regulation, and biodiversity. These ecosystem services, which include carbon sequestration, habitat provision, and improved soil health, are critical benefits of forests that fall outside the boundaries of the current cradle-to-gate analysis. While this LCA focused on production impacts, it is essential to recognize that these broader ecological services should be considered in comprehensive environmental assessments that evaluate the long-term sustainability of construction materials.

Lastly, fossil fuel depletion is considerably lower for cardboard trusses, with a 62% reduction in fossil depletion (2.31×10^0 kg oil eq) compared to timber trusses (6.11×10^0 kg oil eq).

These differences highlight the significant environmental advantages of using cardboard trusses over traditional timber trusses in construction.

5.2. Environmental Impact Contribution of Lifecycle Stages

The environmental impact contribution of lifecycle stages was analyzed from three aspects: (1) comparing the environmental impacts of cardboard truss and timber truss in each lifecycle stage, (2) the environmental impact contribution of each environmental impact category to the total environmental impacts for each lifecycle stage within cardboard truss and timber truss, and (3) the environmental impact contribution of each process of cardboard truss and timber truss.

The environmental impacts of the life cycle stages for both cardboard and timber trusses are compared in Appendix B. The comparison of environmental impacts across life cycle stages for cardboard and timber trusses highlights the clear advantages of the cardboard truss. In terms of climate change, the cardboard truss emits 73% less CO_2 during material manufacturing (7.93×100 kg CO_2 eq vs. 3.02×10^1 kg CO_2 eq for timber), making it much more climate friendly. Additionally, the cardboard truss contributes far less to ozone depletion (2.27×10^{-7} kg CFC-11 eq vs. 1.55×10^{-6} kg CFC-11 eq for timber) and particulate matter formation (1.37×10^{-2} kg $PM_{2.5}$ eq vs. 9.69×10^{-2} kg $PM_{2.5}$ eq for timber), reducing both air pollution and ozone layer damage.

Strikingly, the cardboard truss has an almost negligible agricultural land occupation impact (3.55×10^{-1} m^2a crop eq vs. 1.55×10^3 m^2a crop eq for timber), demonstrating its minimal land use. The cardboard truss also shows lower impacts in terrestrial acidification (84% lower), freshwater eutrophication, and both the freshwater and marine ecotoxicity categories.

In contrast, the timber truss exhibits much higher impacts across key areas like human toxicity (2.69×100 kg 1,4-DB eq vs. 2.21×100 kg for cardboard) and metal depletion, indicating a more significant environmental footprint overall. These results suggest that cardboard trusses are a more sustainable and resource-efficient option compared to traditional timber trusses. However, it is important to note that this analysis focuses only on cradle-to-gate impacts and does not account for the long-term ecological benefits of forests, such as carbon sequestration, biodiversity, and soil conservation, which are essential considerations in evaluating timber's broader environmental role.

The environmental impacts of each life cycle stage for the cardboard and timber trusses were analyzed, focusing on the contribution of each impact category. Figure 4 shows how these impacts are distributed across two key stages: material manufacturing and transportation.

For the cardboard truss during material manufacturing, the largest impact is climate change, making up about 51.75% of the total environmental impact. This is followed by human toxicity (14.16%) and metal depletion (15.01%). Other categories like ozone depletion and water depletion have much smaller contributions. In the transportation stage, climate change remains the most significant impact, accounting for 65.80% of the total, while fossil depletion increases to 21.99%.

For the timber truss, agricultural land occupation dominates the material manufacturing stage, contributing 97.33% of the total environmental impact, highlighting the high land use required for timber production. Other impacts, like climate change (1.90%), human toxicity (0.17%), and metal depletion (0.18%), are much smaller in comparison. However, during transportation, climate change becomes the main concern, making up 65.85% of the total impact, with fossil depletion also being significant at 21.95%.

These results show that for timber trusses, land use is the major issue during manufacturing, while climate change impacts dominate during transportation. These insights can guide where to focus sustainability efforts in both cardboard and timber truss production and distribution.

The analysis focused on evaluating how different processes contribute to selected impact categories. Figure 5 offers a detailed breakdown of the environmental impacts of each specific process within the truss production lifecycle.

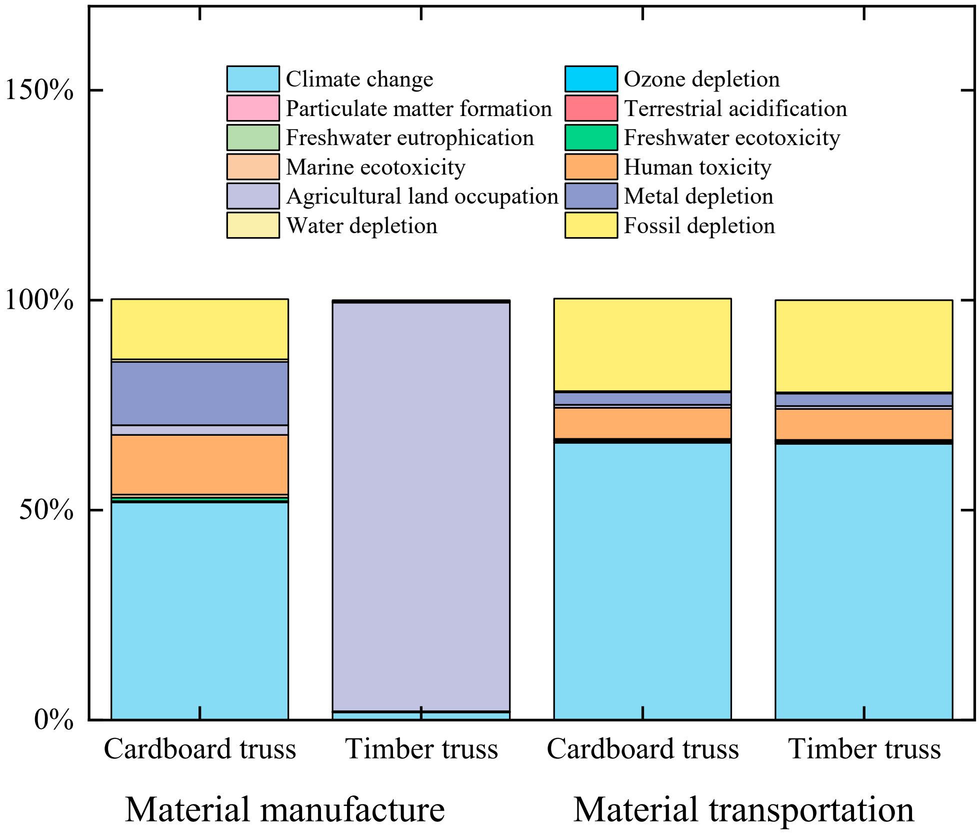

Figure 4. Contribution of each environmental impact category to total environmental impacts for two distinct lifecycle stages.

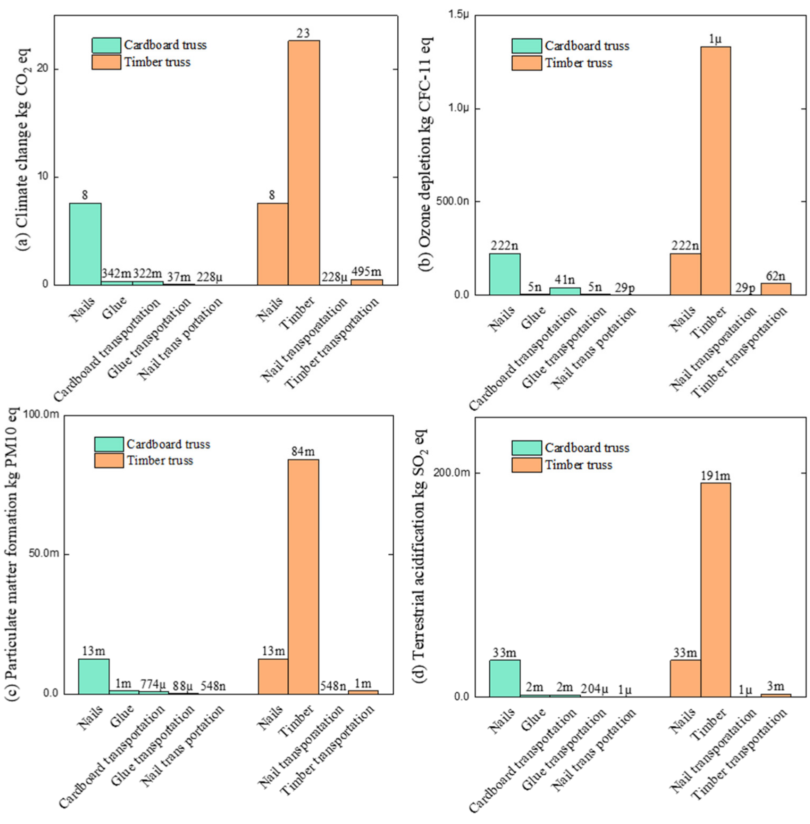

Figure 5. *Cont*.

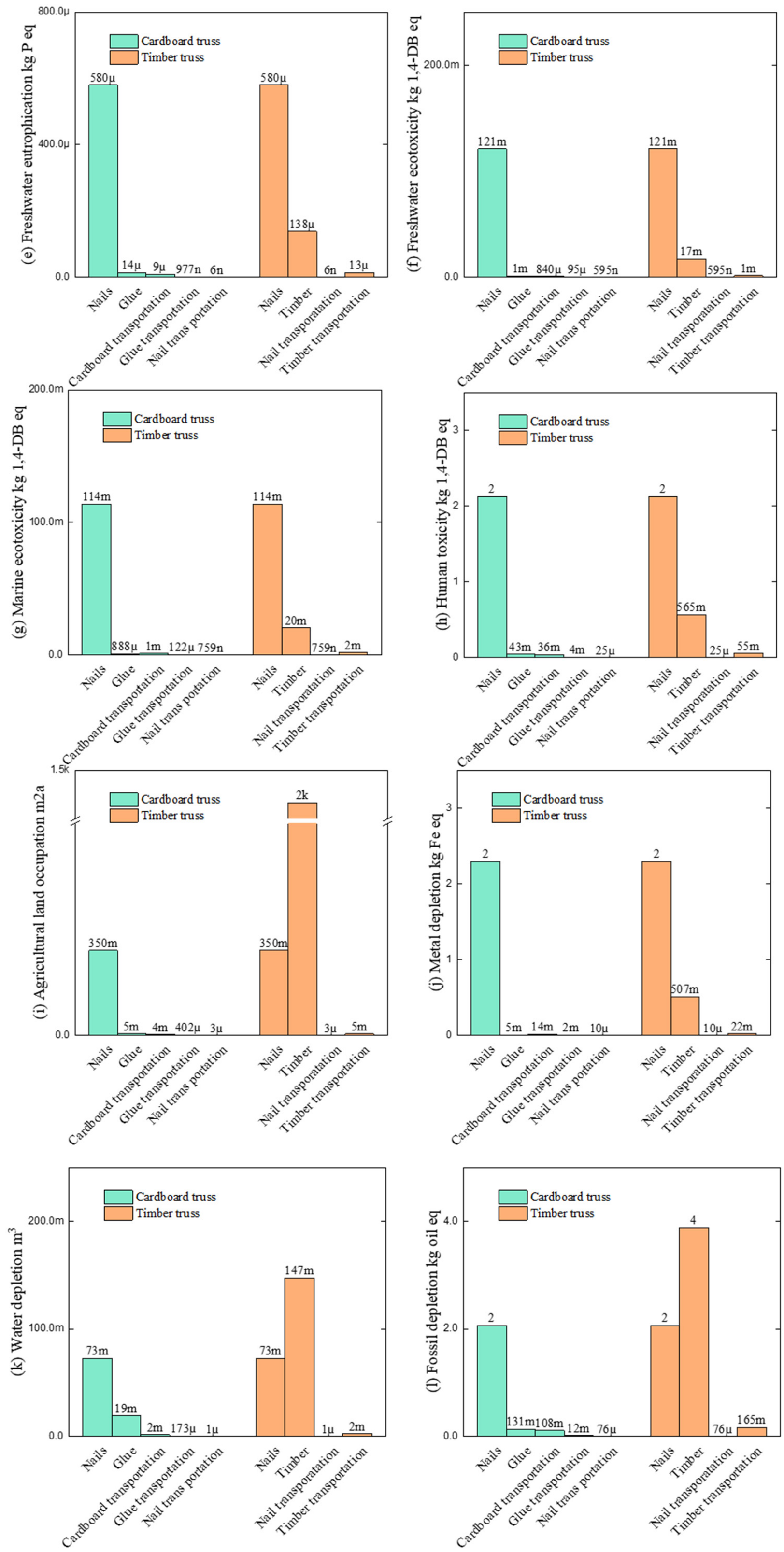

Figure 5. Contribution analysis of cardboard and timber truss corresponding to material manufacturing for (**a**) climate change (kg CO_2 eq), (**b**) ozone depletion (kg CFC-11 eq), (**c**) particulate matter formation (kg $PM_{2.5}$ eq), (**d**) terrestrial acidification (kg SO_2 eq), (**e**) freshwater eutrophication (kg P eq), (**f**) freshwater ecotoxicity (kg 1,4-DB eq), (**g**) marine ecotoxicity (kg 1,4-DB eq), (**h**) human toxicity (kg 1,4-DB eq), (**i**) agricultural land occupation (m^2a eq), (**j**) metal depletion (kg Fe eq), (**k**) water depletion (m^3), and (**l**) fossil depletion (kg oil eq).

For both the cardboard and timber truss scenarios, the production of nails and timber stands out with higher environmental impacts. In the cardboard truss scenario, nail production is the biggest contributor across all impact categories, highlighting its major role in the overall environmental footprint of cardboard trusses. On the other hand, in the timber truss scenario, the timber production process is the primary source of several key impacts, including climate change, ozone depletion, particulate matter formation, terrestrial acidification, land use, water depletion, and fossil fuel use, emphasizing the significant environmental burden associated with timber production.

Additionally, the analysis reveals that nail production also plays a notable role in impact categories like freshwater eutrophication, ecotoxicity, human toxicity, and metal depletion, further contributing to the overall environmental impact in both scenarios.

5.3. Uncertainty Analysis on the Environmental Impact of Cardboard Recycling Process

The uncertainty analysis examines different scenarios where the energy and resource uses for cardboard waste processes—such as collection, sorting, and preparation—are set at 25%, 50%, 75%, and 100% of the levels used in timber material manufacturing. The results, presented in Appendix C, show that even when the energy used for cardboard processing reaches 100% of that for timber, the cardboard truss still has a lower environmental impact than the timber truss in categories like ozone depletion (99.25% of the timber truss) and metal depletion (99.97% of the timber truss). However, in the water depletion category, the cardboard truss exceeds the timber truss by 8.24% (108.24% of the timber truss). In other impact categories, the cardboard truss shows slightly higher impacts than the timber truss. Appendix C shows the uncertainty analysis results of the environmental impact of the cardboard recycling process.

5.4. Benefit Analysis

The benefit analysis in this study is shown in Figure 6. It focuses on evaluating the percentage reduction in environmental impacts when using cardboard trusses instead of traditional timber trusses. The parameters used for this evaluation are based on the environmental categories defined in the ReCiPe midpoint methodology, such as climate change, ozone depletion, and land occupation. In addition to these standard categories, the analysis also considers the benefit of avoiding landfills by diverting waste cardboard to truss production, thereby reducing the environmental burden associated with waste disposal.

The analysis shows that switching to cardboard leads to significant reductions across all impact categories, especially in agricultural land occupation (1500 m^2a eq reduction with 100% benefit), particulate matter formation (83.5 m kg PM10 eq reduction with 74% benefit), terrestrial acidification (189.9 m kg SO_2 eq reduction with 71% benefit), ozone depletion (1.3 μ kg CFC-11 eq reduction with 71% benefit), and climate change (22.4 kg CO_2 eq reduction with 57% benefit).

While the results highlight large land savings, it is important to consider that forests provide additional ecological benefits like soil conservation, water regulation, and biodiversity that are not captured in this analysis. Although the land occupation impact appears unfavorable for timber, these broader ecological contributions are essential factors when evaluating timber’s overall environmental role.

Additionally, cardboard is a waste material that can be recycled, avoiding 33 kg of waste, whereas timber requires natural resources, further supporting the sustainability benefits of cardboard trusses.

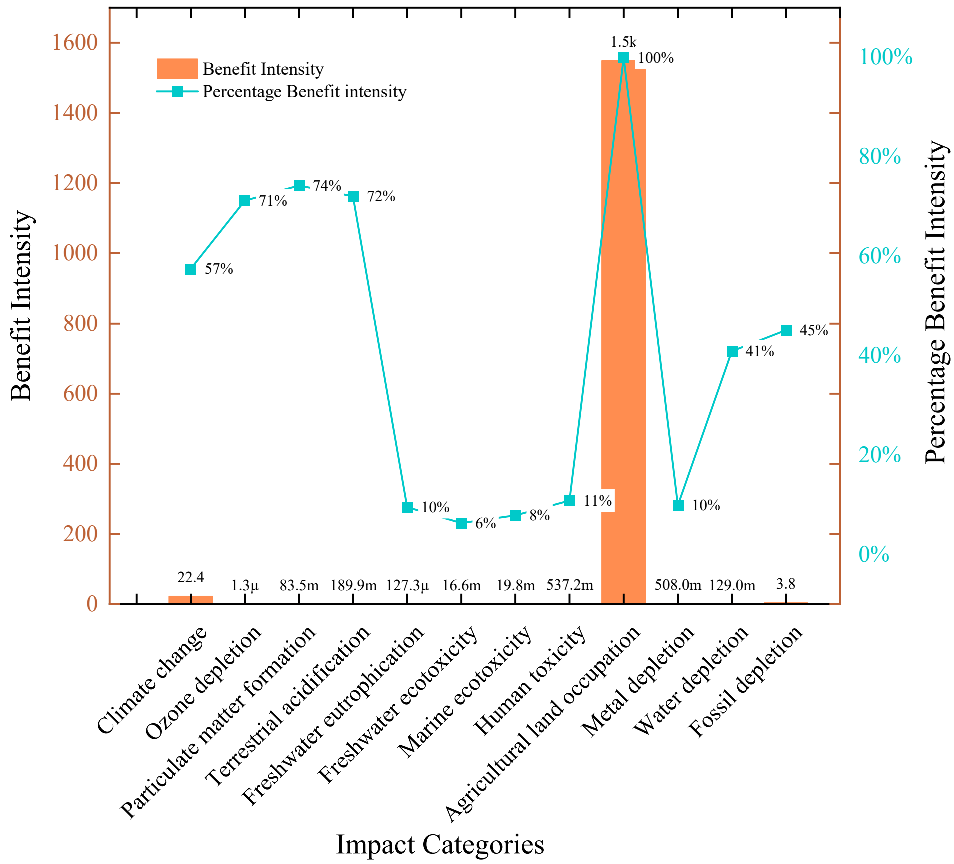

Figure 6. Benefit intensities of carboard and timber truss (units: climate change (kg CO_2 eq), ozone depletion (kg CFC-11 eq), particulate matter formation (kg $PM_{2.5}$ eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), freshwater ecotoxicity (kg 1,4-DB eq), marine ecotoxicity (kg 1,4-DB eq), human toxicity (kg 1,4-DB eq), agricultural land occupation (m^2a crop eq), metal depletion (kg Fe eq), water depletion (m^3), fossil depletion (kg oil eq)).

5.5. Cost Analysis

Cost analysis was undertaken for the phases from the cradle to gate, covering the production of materials, their shipment, and the production of trusses. The parameters include the market prices for materials (e.g., timber), transportation costs, and the associated production costs. Data sources for these parameters were obtained from industry suppliers, local market data in Australia, and relevant cost databases. The recycled cardboard was also considered a zero-cost material since it was sourced from waste streams at recycling centers, as discussed previously. By assessing the prevailing market prices and acquisitions from local suppliers in Australia, the unit expenses for materials and transport were established. The recycled cardboard used in this study was freely acquired from recycling centers, where it is considered waste material rather than a commercial commodity. Therefore, no purchase cost was associated with obtaining the cardboard, as it is not sourced from the market but collected as waste. Timber is priced at AUD 3485 per m^3; glue costs, AUD 43.3 per kg; and nails and other fasteners are priced at AUD 34. Transportation costs are estimated at AUD 0.19 per tonne-kilometer based on the [28]. To calculate truss manufacturing costs, an annual wage of AUD 75,000 is assumed for each worker, with an hourly rate of AUD 44. There are two workers on-site. The manufacturing time for timber trusses is two hours, while cardboard trusses require four hours due to the additional cardboard gluing process. A life cycle cost analysis encompassing material manufacturing, material transportation, and truss manufacture is summarized in Table 3. The unit cost of cardboard trusses is estimated at AUD 214.6, while timber trusses cost AUD 1248.6, representing approximately an 83% reduction when compared to conventional timber truss units. Figure 7 illustrates the cost distribution for each process of cardboard and timber trusses. In the case of cardboard, the material cost only accounts for transportation, which is negligible. In contrast, timber includes both material cost and material transportation. Notably, the timber material cost is significantly higher when compared to cardboard, which is readily available at no cost. However, it is important to note that the cardboard truss incurs a 50% higher labor cost during the manufacturing process compared to the timber truss.

Table 3. Cost analysis for truss manufacture.

Cost (AUD)	Material Manufacture		Material Transportation		Truss Manufacture	
	Cardboard Truss	Timber Truss	Cardboard Truss	Timber Truss	Cardboard Truss	Timber Truss
Timber	0	1124	0	1.53	178.3	89.1
Glue	2.17	0	0.00042	0		
Cardboard	0	0	0.14108	0		
Nails	34	34	0.00952	0.00952		
Total Cost (AUD/truss)	36.2	1157.9	0.2	1.5	178.3	89.1

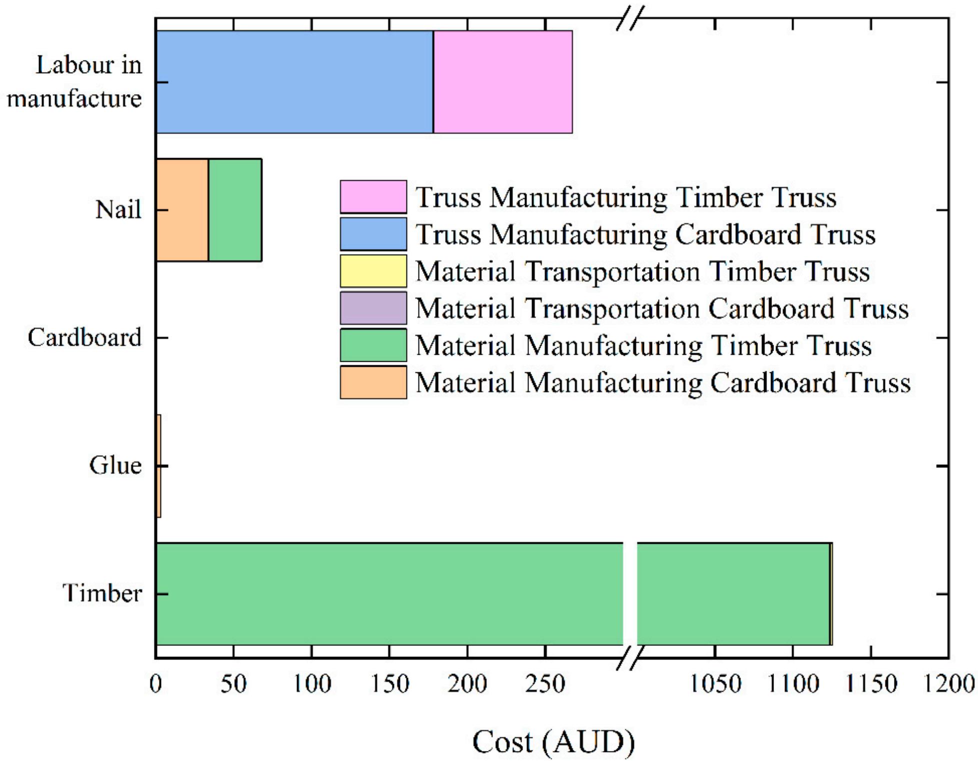

Figure 7. Distribution of cost for cardboard and timber truss.

6. Discussion

The comparative assessment of cardboard and traditional timber trusses revealed that the conventional timber truss exhibited the highest environmental impacts across all the investigated impact categories. This outcome primarily stems from the timber's production phase within the timber truss manufacturing process. The findings underscore that timber constitutes the most significant contributing material in truss production, primarily due to its resource-intensive and energy-intensive manufacturing procedures.

This discovery contradicts the findings of Adhikari and Ozarska [29], who assert that wood is a versatile raw material and the sole renewable construction resource. According to their perspective, the production of wood products and structures consumes minimal energy in comparison to analogous products and structures made from alternative materials. However, this contrast does not extend to recycled materials such as cardboard because the waste material is considered to require zero energy in the raw material manufacturing stage. The same idea is also applied to timber. Timber is a promising material in sustainable construction, often outperforming conventional materials like steel in LCA due to its renewability, carbon sequestration, and lower embodied energy [30,31]. However, when compared to recycled materials like cardboard, timber can lose some of its environmental advantages. Recycled materials benefit from reduced resource extraction and lower energy use, fitting well into circular economy principles. While timber's biodegradability and carbon storage are significant strengths, recycled materials such as cardboard often have lower embodied energy and can be reused more effectively in circular systems, offering distinct advantages in LCA studies [32]. Thus, while timber remains a strong sustainable option, the context of the project—whether it prioritizes low-carbon materials or circular economy practices—plays a critical role in determining the most environmentally favorable choice.

In the conducted benefit analysis, a comparative evaluation was undertaken between cardboard and timber truss production. This assessment maintained consistency with the impact categories used in the initial evaluation. The results of this analysis underscored significant advantages favoring cardboard trusses over their timber counterparts. Noteworthy savings were evident across various impact categories, including a remarkable 100% reduction in agricultural land occupation, a substantial 74% decline in particulate matter formation, and a significant 57% reduction in climate change when opting for cardboard trusses.

From an agricultural land occupation perspective, this study aligns with the findings of [33], which highlighted the strain on land productivity due to modern forestry practices. Bahar, Lo [34] emphasized that timber and fuelwood extraction, as part of agricultural activities, contribute to forest loss and encroach on agricultural land.

Regarding particulate matter formation, pertinent research provides insights into the impact of timber product production on airborne wood particles. As exemplified by Barbosa, Fiedler [35], woodworking shops generate elevated concentrations of these particles, potentially leading to work-related respiratory diseases. Additionally, Milota [36] highlighted that wood drying processes can release volatile organic compounds (VOCs) and hazardous air pollutants (HAPs), including particulate matter.

It is noteworthy that while cardboard trusses offer substantial environmental benefits, reducing land use, emissions, and waste, timber truss production has its own set of considerations. Timber's carbon sequestration capability [29,37] is offset by deforestation's contribution to up to 17% of greenhouse gas emissions [29,38,39]. Furthermore, the transportation of timber products [40], use of chemicals, and wood wastage [41,42] represent additional environmental impacts associated with timber production.

The uncertainty analysis considered both waste collection and sorting upstream, along with recycling downstream. Embodied energy is a critical factor in reusing waste for new products, aligning with Scalisi and Sposito's [43] emphasis on considering embodied energy in building materials for sustainable design choices from the outset. The results show that when the embodied energy of cardboard waste processes equals 100% of timber manufacturing, cardboard trusses are more environmentally favorable than timber in most environmental impact categories.

The utilization of cardboard waste could save 83% cost per truss. Overall, the raw material manufacturing stage of the cardboard truss contributes saving approximately AUD 1121 compared to the timber truss. Also, the reduction in cost in the transportation phases are significant when utilizing the cardboard truss by saving 87% of the transportation cost.

A key limitation of this study is the assumption that recycled cardboard used in construction has no associated cost, which is the current practice. However, at an industrial scale, costs related to collection, processing, and transport might apply, and these were not fully factored into this analysis. Future work should consider including these costs to provide a more realistic economic view. Additionally, this study does not account for the potential differences in the lifespan of cardboard and timber trusses, which could impact both their environmental footprint and long-term costs. Assessing the durability and maintenance needs of each truss type would provide a clearer picture of their overall performance.

7. Limitation, Future Research, and Recommendation

A key limitation of this study is the assumption that recycled cardboard used in construction has no associated cost, which aligns with current practices. However, at an industrial scale, costs related to collection, processing, and transport might apply, and these were not fully factored into this analysis. Future work should consider including these costs to provide a more realistic economic view. Additionally, this study does not account for the potential differences in the lifespan of cardboard and timber trusses, which could impact both their environmental footprint and long-term costs. In this analysis, the assessment excludes considerations of the durability or expected lifespan of both cardboard and timber trusses. As the use of cardboard as a substitute for timber in construction is relatively new, a definitive lifespan has yet to be determined. Assessing the durability and maintenance needs of each truss type would provide a clearer picture of their overall performance, and correlating the lifespan of trusses with LCA outcomes could reveal environmental advantages for future sustainable construction practices.

Addressing energy consumption and the preparation of materials remains a pivotal challenge in the production of trusses. It is recommended that future studies explore strategies to manage energy demands, such as relocating the production of materials and trusses to sites where renewable energy sources are accessible. Additionally, incorporating end-of-life management into environmental impact assessments, including phases like reuse, recovery, and recycling, would contribute to a more comprehensive evaluation of sustainability. These considerations could enhance the understanding of the overall environmental benefits and support the development of more sustainable construction methods.

8. Conclusions

This study shows that cardboard trusses demonstrate remarkable environmental advantages, including a 73% reduction in the climate change impact category, an 83% decrease in ozone-depleting potential, an approximate 85% reduction in particulate matter formation, and nearly 99.98% less agricultural land occupation compared to timber trusses, highlighting the sustainability of cardboard trusses.

Cardboard trusses have climate change as the predominant impact category in both the material manufacturing (51.75%) and material transportation (65.80%) stages, emphasizing the need for emission reduction measures. Timber trusses, on the other hand, heavily rely on agricultural land occupation (97.33%) during material manufacturing and climate change dominate (65.85%) during material transportation.

When considering scenarios where the embodied energy of the cardboard waste collection, sorting, and preparation processes reaches 100% of that of timber material manufacturing, cardboard trusses perform better in ozone depletion (99.25%) and metal depletion (99.97%) but have a higher water depletion impact (108.24%) compared to timber trusses.

Additionally, a benefit analysis shows significant advantages for cardboard trusses, particularly in reducing agricultural land occupation (100% benefit), particulate matter formation (74% benefit), terrestrial acidification (71% benefit), ozone depletion (71% benefit), and climate change (57% benefit), highlighting their landfill avoidance potential.

Lastly, the life cycle cost analysis demonstrates an 83% cost reduction for cardboard trusses (AUD 214.6) compared to timber trusses (AUD 1248.6), although cardboard trusses have a 50% higher labor cost during manufacturing.

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Appendix A

Table A1. Quantified environmental impact values for cardboard truss and conventional timber truss.

Impact Categories	Cardboard Truss	Timber Truss
Climate change (kg CO_2 eq)	8.29×10^{0}	3.07×10^{1}
Ozone depletion (kg CFC-11 eq)	2.72×10^{-7}	1.62×10^{-6}
Particulate matter formation (kg $PM_{2.5}$ eq)	1.45×10^{-2}	9.81×10^{-2}
Terrestrial acidification (kg SO_2 eq)	3.68×10^{-2}	2.27×10^{-1}
Freshwater eutrophication (kg P eq)	6.03×10^{-4}	7.31×10^{-4}
Freshwater ecotoxicity (kg 1,4-DB eq)	1.23×10^{-1}	1.40×10^{-1}
Marine ecotoxicity (kg 1,4-DB eq)	1.16×10^{-1}	1.36×10^{-1}
Human toxicity (kg 1,4-DB eq)	2.21×10^{0}	2.75×10^{0}
Agricultural land occupation (m^2a crop eq)	3.59×10^{-1}	1.55×10^{3}
Metal depletion (kg Fe eq)	2.32×10^{0}	2.83×10^{0}
Fossil depletion (kg oil eq)	2.31×10^{0}	6.11×10^{0}
Water depletion (m^3)	9.32×10^{-2}	2.22×10^{-1}

Appendix B

Table A2. Environmental impacts for cardboard and timber truss of life cycle stages.

Impact Category	Truss Type	Material Manufacturing	Material Transportation
Climate change	Cardboard Truss	7.93×10^{0}	3.59×10^{-1}
	Timber Truss	3.02×10^{1}	4.95×10^{-1}
Ozone depletion	Cardboard Truss	2.27×10^{-7}	4.52×10^{-8}
	Timber Truss	1.55×10^{-6}	6.23×10^{-8}
Particulate matter formation	Cardboard Truss	1.37×10^{-2}	8.62×10^{-4}
	Timber Truss	9.69×10^{-2}	1.19×10^{-3}
Terrestrial acidification	Cardboard Truss	3.48×10^{-2}	2.00×10^{-3}
	Timber Truss	2.24×10^{-1}	2.76×10^{-3}
Freshwater eutrophication	Cardboard Truss	5.94×10^{-4}	9.58×10^{-6}
	Timber Truss	7.18×10^{-4}	1.32×10^{-5}
Freshwater ecotoxicity	Cardboard Truss	1.22×10^{-1}	9.36×10^{-4}
	Timber Truss	1.38×10^{-1}	1.29×10^{-3}
Marine ecotoxicity	Cardboard Truss	1.15×10^{-1}	1.19×10^{-3}
	Timber Truss	1.34×10^{-1}	1.65×10^{-3}
Human toxicity	Cardboard Truss	2.17×10^{0}	4.01×10^{-2}
	Timber Truss	2.69×10^{0}	5.52×10^{-2}
Agricultural land occupation	Cardboard Truss	3.55×10^{-1}	3.94×10^{-3}
	Timber Truss	1.55×10^{3}	5.43×10^{-3}
Metal depletion	Cardboard Truss	2.30×10^{0}	1.59×10^{-2}
	Timber Truss	2.80×10^{0}	2.19×10^{-2}
Water depletion	Cardboard Truss	9.15×10^{-2}	1.69×10^{-3}
	Timber Truss	2.20×10^{-1}	2.33×10^{-3}
Fossil depletion	Cardboard Truss	2.19×10^{0}	1.20×10^{-1}
	Timber Truss	5.94×10^{0}	1.65×10^{-1}

Units: Climate change (kg CO_2 eq), Ozone depletion (kg CFC-11 eq), Particulate matter formation (kg $PM_{2.5}$ eq), Terrestrial acidification (kg SO_2 eq), Freshwater eutrophication (kg P eq), Freshwater ecotoxicity (kg 1,4-DB eq), Marine ecotoxicity (kg 1,4-DB eq), Human toxicity (kg 1,4-DB eq), Agricultural land occupation (m^2a), Metal depletion (kg Fe eq), Water depletion (m^3), and Fossil depletion (kg oil eq).

Appendix C

Table A3. The uncertainty analysis of the environmental impact of the cardboard recycling process.

Impact Categories		Cardboard Truss	+25%	+50%	+75%	+100%	Timber Truss
		Cardboard Truss/ Timber Truss	+25%/ Timber Truss	+50%/ Timber Truss	+75%/ Timber Truss	+100%/ Timber Truss	Timber Truss/ Timber Truss
Climate change	(kg CO_2 eq)	8.29×10^0	1.39×10^1	1.96×10^1	2.52×10^1	3.09×10^1	3.07×10^1
	%	27.01	45.42	63.84	82.26	100.67	100
Ozone depletion	(kg CFC-11 eq)	2.72×10^{-7}	6.05×10^{-7}	9.39×10^{-7}	1.27×10^{-6}	1.61×10^{-6}	1.62×10^{-6}
	%	16.83	37.44	58.04	78.65	99.25	100
Particulate matter formation	(kg $PM_{2.5}$ eq)	1.45×10^{-2}	3.56×10^{-2}	5.67×10^{-2}	7.77×10^{-2}	9.88×10^{-2}	9.81×10^{-2}
	%	14.81	36.29	57.77	79.25	100.73	100
Terrestrial acidification	(kg SO_2 eq)	3.68×10^{-2}	8.46×10^{-2}	1.32×10^{-1}	1.80×10^{-1}	2.28×10^{-1}	2.27×10^{-1}
	%	16.24	37.30	58.37	79.43	100.50	100%
Freshwater eutrophication	(kg P eq)	6.03×10^{-4}	6.38×10^{-4}	6.72×10^{-4}	7.07×10^{-4}	7.41×10^{-4}	7.31×10^{-4}
	%	82.59	87.29	92.00	96.71	101.42	100
Freshwater ecotoxicity	(kg 1,4-DB eq)	1.23×10^{-1}	1.27×10^{-1}	1.32×10^{-1}	1.36×10^{-1}	1.40×10^{-1}	1.40×10^{-1}
	%	88.12	91.21	94.30	97.39	100.48	100
Marine ecotoxicity	(kg 1,4-DB eq)	1.16×10^{-1}	1.21×10^{-1}	1.26×10^{-1}	1.31×10^{-1}	1.36×10^{-1}	1.36×10^{-1}
	%	85.41	89.14	92.87	96.59	100.32	100
Human toxicity	(kg 1,4-DB eq)	2.21×10^0	2.35×10^0	2.49×10^0	2.64×10^0	2.78×10^0	2.75×10^0
	%	80.46	85.59	90.73	95.87	101.00	100
Agricultural land occupation	(m^2a eq)	3.59×10^{-1}	3.87×10^2	7.74×10^2	1.16×10^3	1.55×10^3	1.55×10^3
	%	0.02	25.02	50.01	75.01	100.00	100
Metal depletion	(kg Fe eq)	2.32×10^0	2.45×10^0	2.57×10^0	2.70×10^0	2.83×10^0	2.83×10^0
	%	82.03	86.51	91.00	95.48	99.97	100
Water depletion	(m^3)	2.31×10^0	3.28×10^0	4.25×10^0	5.22×10^0	6.19×10^0	6.11×10^0
	%	41.95	58.52	75.10	91.67	108.24	100
Fossil depletion	(kg oil eq)	9.32×10^{-2}	1.30×10^{-1}	1.67×10^{-1}	2.04×10^{-1}	2.41×10^{-1}	2.22×10^{-1}
	%	37.85	53.74	69.63	85.51	101.40	100

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