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Evaluating the Structural and Environmental Performance of Bio-Based Construction Materials for Green Buildings

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Abstract. Numerous circular start-ups engaged in the bio-construction sector develop novel substances and building goods, such as plant-based insulation supplies, bio-bricks, thermo-acoustic insulating sheets, screeds, and materials. They employ local agricultural products, like hemp, and by-products, including wheat straw, rice straw, rice husks, and food scraps, as substitutes for traditional construction supplies, goods, and procedures. In some instances, these goods are accredited with a Declaration of Environment or by the accreditation unique to bio-construction materials, providing several advantages, including technical, aesthetic, ecological, health, social, and comfort benefits. This research delineates the identified Construction Supply Units (CSUs)functioning in the bio-construction sector, detailing the features of their operations and the bio-materials and goods they provide. The findings of the literature study on ecological information on certain bio-materials and goods are provided and analysed. This information will be instrumental in advancing subsequent phases of the comprehensive research, specifically the Life Cycle Assessment (LCA) of the bio-construction materials and goods from the chosen CSUs. The present study has provided preliminary findings from visualizing the building industry, qualitative interviews, and literature reviews.

1 Introduction

The transition to Circular Economy (CE) [1] poses a major challenge to the construction industry, which can alleviate its environmental consequences and enhance the socio-economic development. The industry of construction consumes significant raw materials and contributes approximately 42 % of the global carbon emissions [12]. Debris in building and construction is also a major part of the solid waste that is produced in the world as about 32 % of the total [9].

Construction Supply Units (CSUs) are the units that contribute to the shift towards the circular economy since they are creative with the use of local agricultural by-products of wheat and rice straws that are economical in the extraction of virgin materials and land utilization. The bio-based building materials not only assist in managing wastes, but also have the socio-economic benefits on the surrounding communities where they are in operation [3]. In spite of these benefits, this sector of construction has been lagging in adopting this kind of innovation in green building [2][4]. The CSUs discussed by the researchers are using construction materials that are aimed at reusing the local farming waste products, i.e. the wheat straw and rice straws, thus reducing the extraction of virgin materials, reducing land use, and create positive impacts, especially to the local communities where the CSUs are located.

This paper offers the early findings of ongoing research aimed at enhancing the knowledge of the CSUs functioning within the bio-construction sector, as well as the environmental implications and efficacy of their building materials [10] [13]. the study seeks to investigate the organization of circular creativity within the building-related communities of the chosen CSU and the affiliations with the prominent big enterprises within those environments in green building [5].

This paper will address this gap by assessing the environmental implications of bio-based construction materials using Life Cycle Assessment (LCA), including such materials as a rice husk panel and hempcrete. The study examines the socio-economic value of CSUs and how they help to enhance the building sector in circles.

Research Questions:

RQ1: How do bio-based building materials using local agricultural waste materials including hemp and rice straw perform in terms of environmental performance compared to the conventional building materials used in green building projects?

RQ2: What is the way to ensure that circular economy models, applied by Construction Supply Units (CSUs), can improve sustainability and economic feasibility of bio-based construction materials in the building industry?

RQ3: What are the socio-economic values of the use of bio-based construction materials in the communities,

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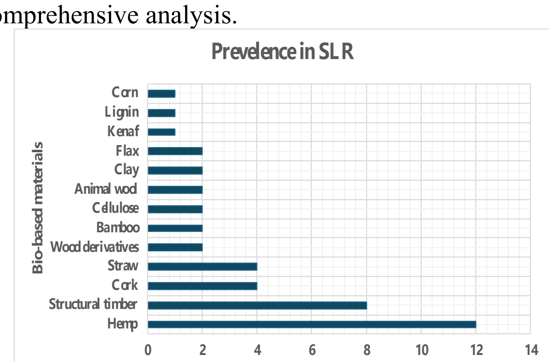
and how they can diminish the overall sustainability targets of the construction sector?

Novelty of the Study:

The paper presents the application of the Life Cycle Assessment (LCA) approach with the emphasis on bio-based construction products made of rice husk as a type of agricultural by-products, which have not been thoroughly researched regarding the green building. The originality of this study is in the fact that an LCA tool is effectively used to assess the environmental benefits of these new bio-composites, which is also critical in the context of their sustainability. Besides, the social dimension of the construction supply units (CSUs) is considered in this study considering both the qualitative data of the interviews with CSU pioneers and provides a special point of view on the socio-economic processes of working with bio-based materials. This combination of social assessment and technical LCA analysis provides this research with a gap in the current knowledge about both the environmental and community-level effects of bio-based building materials.

2 Background

A comprehensive assessment of advanced bio-based construction supplies was conducted, including two sections [8]. An organized review examined the status of studies. A web search investigated the bio-based substances and goods accessible in the marketplace and those that are frequently utilized [14]. In the review, the sources ScienceDirect and Scopus were queried for: [("bio-based elements" OR "biobased elements") AND (structures OR building)]. The preliminary search yielded a total of 85 publications after the elimination of duplicates in the green building. A selection was made from this initial collection based on the following standards: it has one or more bio-based elements; the substance is suitable for the framework or exterior of a domestic or mixed-use project; the article discusses the embedded consequences of the building component. This culminated in 24 research articles for comprehensive analysis.



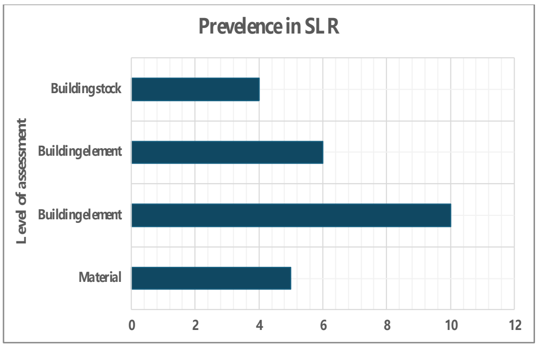


Fig. 1. Prevalence in SLR analysis: a) Bio-based materials, b) Level of assessment

Fig. 1 (a) illustrates the range of bio-based building supplies discussed in the 24 chosen publications, indicating various active research into using bio-based substances in building. Fig. 1 (b) illustrates the level at which the items in Fig. 1 (a) were evaluated. Thus, the integration of these descriptions offered an initial overview of the items deemed pertinent to the aims of this research. Among the 24 publications, 19 examine a bio-composite, including one of the bio-based components shown in Fig. 1 (a) and a non-bio-based adhesive. Most of these investigations included experimentation with material composition and evaluating their qualities in green buildings. These investigations indicate favourable outcomes for sustainability and thermal and mechanical qualities; knowledge about other factors, such as longevity and resistance to fire, remains limited. The particular test bio-composites were deemed outside the scope.

Fig. 1 (a) indicates that hemp is the most extensively researched material, with 12 studies focusing on hempcrete, which accounts for nine of those studies. Eight articles evaluated hemp at the building component level, whereas one research study analysed it at the building level. All studies endorse the use of hemp as a sustainable building material. Among all bio-composites discussed in the articles, hempcrete is the only one that has shown suitability as a building material. At the same time, the remainder remains subject to modification and experimentation at the material level in green building. Structural lumber was used multiple times as a hemp concrete wall framework, resulting in little consideration of its characteristics or ecological efficiency.

It is inferred that it functions well with bio-based filler materials. Wheat and cork are the third most researched materials; each analysed four times. Cork is deemed beyond the scope due to its comparatively greater traveling distance. Straw was discovered in conventional straw bales, compressed straw, or amalgamated with cement. Sand building methods are now being modified to adapt to industrialisation [6]. It is often contended that traditional building methods using certain organic substances (e.g., traditional straw bale building) cannot compete with novel approaches regarding application, quality assurance, labour costs, and overall affordability. Innovative materials and methodologies are being created, like bio-composites and tailored bio-based goods [11]. These offer low-impact alternatives competing with industrial products and processes (e.g., steel, cement). Following this first assessment, the researchers resolved to investigate the use of lumber, hemp, and straw within building practices more thoroughly.

3 Proposed Structural and Environmental Performance of Bio-Based Construction Materials

3.1 Methodological Framework

The tool is an Excel-based Life Cycle Assessment (LCA) [7] instrument for structures, particularly designed for the construction industry. It illustrates the hierarchical framework of the modeling process inside the tool: components - work segments - structural components - edifices. Initially, supplies are characterized by defining their thermal transmission factor (2) and volume (p), while associating them with the Life Cycle Inventory (LCI) [15] historical information for production stages (A1-A3), transportation (A4), and end-of-life phases (C2, C3, C4), according to scenarios in green building. Secondly, work sections are delineated by their material makeup and corresponding amounts per unit work segment (e.g., m² wall). The work section specification includes possibilities for building processes (A5), sanitation, upkeep, and repairs (B2, B4), as well as demolition (C1). Third, structural components are represented as a collection of work sections. This investigation is confined to the building element level; hence, the ultimate upscaling to structures is excluded from this work.

3.2 Evaluation Methodology

The different parts are elaborated on in further depth below.

Objective and parameters: The aim is to calculate the life cycle environmental impacts of the chosen technology for the different building components: exterior walls (EW), inside walls (IW), the first floor (FF), inner floors (IF), flat roofing (FR), and roof pitches (PR). Impacts are examined across all types and against traditional remedies. This approach reviews the performance of bio-based products in every category of effects compared to conventional materials, highlighting the characteristics (i.e., life cycle phases and work portions) that add most significantly to each category.

Table 1. CED impact analysis

Impact category	Natural aggregate concrete	Recycled aggregate concrete	Green concrete (30%)	Green concrete (20%)	Green concrete (10%)
NR, fossil	1637.378	1139.675	768.435	758.277	747.146
NR, nuclear	218.353	166.137	111.546	111.189	110.53
NR, biomass	1.051	1.497	1.496	2.236	1.959
R, biomass	43.374	41.488	385.752	267.717	147.739
R (wind, solar, geothermal)	22.728	18.756	12.479	13.387	13.527
R, water	47.069	37.814	27.165	27.754	27.919
Total	1969.953	1405.367	1306.873	1180.56	1048.82

Operational unit: For EW, FF, FR, and PR, the Functional Area (FA) is 1 m² of the corresponding building component with a thermal transmittance (U) of 0.20 W/m²K, according to the passive house criteria. For IW, there are no requirements about thermal transparency. The FA is defined as 1 m² of building component exhibiting comparable insulation properties, namely a sound attenuation index of roughly 42 dB for walls with loads and 38 dB for non-bearing buildings. The structural elements are dimensioned to ensure that all parts are physically viable for their intended applications in the subsequent case investigations. Finally, building thermodynamics is considered, indicating that water and air barriers are necessary to prevent penetration and interior condensate in a green building.

Parameters of the system: The LCA phases referenced and included are A1-A3 (Product phase), A4-A5 (Building process phase), B2 (Upkeep), B4 (substitution), and C1-C4 (End of life phase). B2 is separated into B2.1 (Picking), B2.2 (Minor Maintenance), and B2.3 (Major Maintenance). B4 pertains only to the building component level, namely B4.1 (Replacement job component) in green building.

Biogenic carbon fluxes: Naturally occurring carbon (C) is becoming increasingly significant in bio-based structures. The research uses the 0/0 strategy in this work, meaning neither biogenic carbon sequestration nor emissions are included in the life cycle assessment's index. A straightforward, static assessment of biogenic carbon in construction elements is conducted, relying on the kilograms of bio-based materials per architectural element as documented in the literature. The estimate accounts for biogenic carbon in the bio-based components and insulating materials, excluding finishing and support components in the green building. The natural carbon content of lumber varies across species, although a typical approximation is 0.5 kgC/kg lumber.

4 Discussions

The research delineates the chosen CSUs, indicating their year of establishment, geographical location, and pertinent production information. All four regions maintain robust agricultural output, despite the significant impact of industrialisation on their economies. Conversations with some CSU pioneers are continuing and seek to elucidate their vision, enhance understanding of their production, and assess their function within the local community and the broader industrial environment in green building. The conversations reveal the ethically and socially creative bio-based manufacturing methods and end products established by the CSUs. These provide a chance to capitalize on local crop residue and prevent its destruction or the burning process, thereby addressing local environmental challenges.

This paper analyzed the environmental and socio-economic effects of bio-based construction material of the selected Construction Supply Units (CSUs) and compared the materials to the traditional building products. The findings of the research have shown a number of major findings:

Green Performance of Bio-Based Materials

The Life Cycle Assessment (LCA) done on the bio-based materials namely, rice husk panels, hempcrete and wheat straw composites indicated that these materials tend to provide major curtailment in the carbon emissions and energy expenditure of the conventional materials such as cement and steel. An example is the use of rice husk panels which showed a smaller Cumulative Energy Demand (CED) and global warming potential (GWP). Table 1 and Table 2 show that rice husk panels had a lower potential of CED as well as global warming. This implies that incorporation of a waste produced by the agricultural activities in the construction may significantly lower the environmental impact of the building sector.

Socio-Economic Effect of CSUs

The qualitative interviews that were conducted with the pioneers of CSU showed that not only are these organizations promoting sustainable ways of building but they are also promoting the development of the local economy. The reusing of the agricultural by-products by the CSUs is generating employment and boosting the lives of the local farmers. As well, such efforts enhance environmental education and involvement of local community in the activities of sustainability, which fosters the feeling of ownership and environmental responsibility.

Bio- Based vs. Traditional **material Analysis**

In the comparison of bio-based materials such as rice husk panels with conventional materials, the study revealed that bio-based materials have lower impact on the environment as a whole, but it has got problems in cost-effectiveness and material performance. As one example, even though hempcrete has proven to be a good thermal insulator, it does not have the resistance to fire that is achieved with traditional building materials, such as concrete. The findings are important in dictating future studies to optimize the performance of bio-based materials without compromising its environmental superiority.

CSUs and their Social Impact

In the research, the selected CSUs are outlined, providing a year of its foundation, geographical area, and relevant information about its production. The four regions also are working with strong agricultural production, although the industrialization has played a great role in the economies of the regions. The interviews with CSU innovators have been aimed to gain the clearness regarding their vision and production technology, and how they can fit into local communities and the industrial context. These discussions unveil the ethically and socially creative means of manufacturing bio-based products and their final products that these CSUs have put in place. The CSUs utilize the local crop residue, instead of destroying it or burning it, and therefore, mitigate local environmental problems. This is in line with the overall sustainability in the bio-construction industry.

Global Warming and CED Analysis

The research also gives results of literature review on the ecological impact of building materials including traditional and bio-based materials through Cumulative Energy Demand (CED). This environmental data will prove useful in the future LCA undertaking to assess the impacts of materials obtained using the selected CSUs. Table 1 and table 2 represent the effects of CED of traditional, recycled, and green concrete mix. As an example, the energy costs of using traditional concrete with natural aggregates are the greatest, and the costs of using concrete based on recycled stones and green concrete materials (e.g., hemp waste) are lower.

The research provides the findings from a literature review analyzing research on the ecological effects of traditional and bio-based building supplies using Cumulative Energy Demand (CED) in green building. This environmental information will be necessary for conducting a future LCA to evaluate the consequences of goods and materials derived from the chosen CSUs. Table 1 displays the findings of the research that examined the CED effects of typical, recycled, and green concrete mixes for Renewable Energy (R) and Non-Renewable Energy (NR). The study indicates that traditional concrete composed of natural aggregates incurs the highest energy expenses, in contrast to concrete derived from reused stones and green concrete materials (contingent upon the distribution of power costs to hemp waste products).

Table 2. Global warming & CED analysis

Impact	Global warming potential	CED
Rice husk	1.21	2.76
Cork scraps	2.86	8.21
Granulated rubber	3.42	1.34
Coffee chaff	0.64	9.32
Waste chaff	7.45	1.86
Waste paper1	4.65	1.68
Waste paper2	3.54	1.64
Waste paper3	3.84	1.89

Table 2 presents the findings for a 1 m^2 panel constructed from reused components. The expected contribution to global warming was minor for panels manufactured from rice husk (2.32 kg CO2 eq.) and bean chaff (0.67 kg CO2 eq.). When accounting for noise absorption and heat resistance, the effects on global warming and CED were less for the husks of rice and bean chaff panels and the panel composed of wood fibers and trash paper, compared to the remaining panels in the green building.

5 Conclusion

The first findings of this research indicate that the sample of the chosen CSUs was derived from the geographical representation of the building sector. The data gathered from the interviews with the chosen CUs pertained to the attributes of their activity and new biomaterials and services in green buildings. The review underscores the advantages of the examined bio-based building materials and products regarding reduced effects compared to traditional alternatives. The assessment of the goods from the chosen CSUs indicates the potential for implementing cleaner production practices in the construction industry, which might diminish landfill disposal or incineration of local waste and enhance their value within more sustainable supply chains. The findings demonstrate the potential for a business to recuperate bio-materials and the absence of insurmountable economic barriers due to creative methods and a commitment to fostering an entrepreneurial spirit that benefits the local ecosystem. Only a restricted array of biomolecules and goods has been examined in the study, which is essential for establishing an initial set of ecological information necessary for assessing the biological materials and goods of the chosen CSU using LCA in green building.

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