Affordable Wall Panels Using Sustainable Waste Materials: A Review

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ABSTRACT
With the enormous population growth in the last few decades, there is a demand for infrastructure development and rapid urbanization that result in the depletion of natural resources, emission of greenhouse gases, and subsequently, exacerbation of the climate crisis. Moreover, waste materials generated by different industries such as the construction industry end up by burning or dumping them in landfills further posing serious health hazards. Besides, skyrocketing prices of housing and limited income of major population groups have resulted in the housing crisis. Therefore, it is imperative to find low-cost, environment friendly and sustainable solutions to mitigate aforementioned problems. The literature indicates that the modular construction method could be a viable solution that can reduce waste generation and construction costs. This method has been extensively used in many parts of the world in different applications mostly in the construction of low-rise buildings. However, with the advent of technological advancement in the construction industry, studies have shown that modular construction can also be successfully employed for medium and high-rise buildings. This paper presents a holistic review of the existing literature on the development of modular wall panels to foster sustainability and alleviate the housing gap. To this end, a proactive approach has been undertaken to identify key research areas to study the use of waste materials in the development of modular wall panels. The results of the literature review revealed that modular wall panels have the potential to substantially reduce the construction cost and carbon footprint. The barriers to the growth of modular construction were also discussed in this paper.

KEYWORDS
Offsite construction, Modular construction; Prefabricated wall panels, Sustainability

INTRODUCTION
By 2031, Canada will require 3.5 million new housing units according to an assessment by Canada Mortgage and Housing Corporation (CMHC). In order to cater to this requirement, the government of Canada under the aegis of the National Housing Strategy (NHS) has announced an investment of 72 billion dollars to build up to 160,000 new housing units by 2027 (CMHC, 2017). Also, it has launched a rapid housing initiative in 2020 to construct 10,000 new residential units with a total investment of 2.5 billion dollars in order to meet the housing needs of its vulnerable citizens. Further, the government of Canada has created a net-zero accelerator fund with the investment of 8 billion dollars to combat climate change by achieving net-zero emissions by 2050. There is a pressing need for innovative sustainable alternatives to address affordable housing and greener

construction. Modular construction could be a viable solution to chronic homelessness and climate ambitions due to its cost-effectiveness, rapid construction time, better quality control, lower carbon emissions and higher energy efficiency (Kamali et al., 2016). In a survey conducted by Qin and Yao (2020) modular construction accounts for more than 30% of multifamily residential buildings. It could be a potential solution for temporary housing in case of a humanitarian catastrophe such as earthquakes, floods, hurricanes, among others (Pérez et al., 2021). Its demand has also gained momentum in this era of the pandemic to build isolation units and quarantine centers.

Modular wall panels are prefabricated panels that are manufactured away from the construction site in the form of modules under a controlled environment and then transported to the building's final location for installation. Wall panels usually consist of a core of insulation material such as polyurethane, polystyrene, glass fibers and skin and laminate of structural boards (Batouli and Zhu, 2013). However, these synthetic insulation materials are not biodegradable and have a substantial negative impact on the environment (Wimmers et al., 2019).

Previous studies conducted emphasized either on the modular construction techniques to achieve affordable housing or the development of insulation materials by recycling the waste materials. But very limited literature is available involving the utilization of waste materials in modular construction. Therefore, this study conducted a literature review to investigate the incorporation of sustainable waste materials in the production of prefabricated wall panels. An attempt was also made to elucidate the benefits of waste-based construction materials as compared to conventional materials. The possible outcomes of this review can help in achieving sustainable development goals by integrating effective waste management and ecofriendly construction practices.

METHODOLOGY

In this study, different documents that have been published between the years 2012 and 2022 were compiled and reviewed. The Compendex and Geobase databases of Engineering Village and ASCE Library database were used for the search and extraction of relevant documents. These comprehensive databases were selected because they contain millions of peer-reviewed, highly indexed and most updated international research articles (ELSEVIER, 2022; ASCE, 2022). The documents were compiled using suitable keywords including “modular construction”, “modular walls”, “prefabricated panels” and “sustainable construction”. A significant amount of research work was found in the form of journal articles, conference proceedings, press articles, book chapters and organizational reports. Through a screening process, the found documents were scrutinized first by the relevance of their titles and then by reviewing their abstracts and conclusions. The documents were then further refined by synthesizing the whole document and finally, the most relevant sources were selected for review. The government websites such as National Housing Strategy and Net Zero Accelerator Initiative were also searched to retrieve the suitable reports about the various updated policies and strategies related to the climate change, housing and construction industry (CMHC, 2017; GOC, 2022). The total number of relevant documents found during the preliminary search process is presented in Table1.

Table 1. Documents found during preliminary search process

Type of Document	No. of Documents
Journal Articles	28
Conference Proceedings/Book Chapters	18
Organizational Reports	12

However, based on the further pursuance of the aforementioned screening process, out of these searched documents ten documents, enumerated in Table 2, were found most relevant to the scope of this research and have been discussed in detail in the following section.

RESULTS AND DISCUSSION

Table 2 lists the most relevant documents reviewed in this paper. The results of reviewing each of these documents have been presented in this section. It should be mentioned that, due to space limitations, only the main findings have been reported.

Table 2. Different sustainable waste materials available in the literature

S.No.	Author	Year	Location	Material Used	Property Investigated
1	Benallel et al.	2021	Morocco	Recycled Cardboard and Vegetable Fibers	Thermal Conductivity and Water Absorption
	Gößwald et al.	2021	Austria	Spruce Bark Fibres	Thermal Conductivity and Water Absorption
3	Sezgin et al.	2021	Turkey	Recycled Cotton Fibers and Packaging wastes	Thermal Resistance and Sound Absorption
4	Ali et al.	2021	Saudi Arabia	Date Palm Leaves and Wheat Straw	Thermal Conductivity and Sound Absorption
5	Wimmers et al.	2019	Canada	Wood Shavings and Filamentous Fungi	Thermal Conductivity
6	Beaudry and MacDougall	2019	Canada	Wheat Straw Bale	Axial Compression and Out of Plane Bending
7	Jami et al.	2019	India	Hemp	NA
8	Suskiyatno et al.	2018	Indonesia	Waste Paper and cassava (tapioca)	Water Resistance
9	CoDyre and Fam	2017	Canada	Flax Fiber	Compressive Strength
10	Batouli and Zhu	2013	United States	Kenaf Fibers	Environmental Impacts

Benallel et al. (2021): In a work by Benallel et al. (2021) innovative thermal insulation material was developed with the help of recycled cardboard wastes and four different types of plant fibers (i.e. reed, alfa, fig branches and olive leaves). The crushed cardboard waste was used as a binder and its percentage proportion was varied from 60 to 20% by weight. The washed and perfectly dried plant fibers were first crushed and sieved to get the fibers that were 5mm in length and 2mm in diameter and then mixed with the binder. The scanning electron microscopy (SEM) analysis, fourier transformation infrared (FTIR) and X-ray diffraction were also conducted to determine the microstructure, spectral transmittance and crystallinity index. It was reported that the surface of fibers was porous, a wide band was present ranging from 3600 to 3000 cm^{-1} and Alfa tree fibers had the highest crystallinity index about 46%. With the increasing amount of fibers, both density and thermal conductivity were increased whereas water absorption rate was reduced for all types of plant fibers. Alfa fibers were found to have the lowest thermal conductivity for a 60% mass fraction of cardboard waste. It was concluded that all the studied composites have better insulation characteristics and lesser environmental implications as compared to traditional insulation materials.

Gößwald et al. (2021): Gößwald and his co-researchers conducted a research to investigate the potential of bark fibers from spruce trees of the species Picea abies to manufacture the thermal insulation panels without using adhesives. The fiberboards were prepared using the wet process with fibers of different lengths such as 1.6mm, 4mm and 7mm and different densities varying between (204-277) kg/m^3. The influence of length and density of fibers on thermal conductivity, thickness swelling and water absorption were evaluated. It was noticed that thermal conductivity, thickness swelling and water absorption increase with the density but the influence of fiber length was insignificant. The thermal conductivity of the insulation panels was found to be 15% higher in comparison to mineral wool and polystyrene. The maximum and minimum water absorption after 24 hours was found to be 380% and 55% respectively whereas the thickness swelling after 24 hours was less than 25%. Thus, based on the results obtained the authors recommended that spruce bark fibers can be utilized in the production of eco-friendly thermal insulation panels.

Sezgin et al. (2021): In another research, Sezgin et al. (2021) devised a 100% recycled composite panel by utilizing wastes from two different sectors namely, the textile and food & packaging industries. The cotton fibers of waste denim in the form of reinforcement material were combined with matrix materials such as polypropylene and polyethylene waste products (e.g. bottle caps, food, and cleaning containers). The composite panels of different thicknesses (5,10 and 20mm) were prepared by mixing the cotton fibers with the grounded matrix material of granule size between 1 and 5mm, in a percentage proportion of 30%, using a hot press process. The results showed that the density of panels decreased with the increase in thickness of panels due to the presence of air gaps in the pores of composite. However, the thinnest panel was found to be hydrophobic due to its high contact angles caused by the covering of the plastic layer formed under high pressures. Air permeability, porosity, sound absorption and thermal resistance were increased with the increase in panel thickness. It is due to the energy scattering caused by the resistance of air gaps in the pores. The authors reported that recycled composite panels can be used as a sustainable alternative for the replacement of conventional insulation materials because of their waste reduction, energy efficiency and cost-effectiveness.

Ali et al. (2021): Ali et al. (2021) developed fiberboards using agricultural waste of date palm tree leaves and wheat straw husk to investigate the thermal insulation and sound absorption characteristics. A total of ten fiberboards were prepared of size (300mm x 300mm) with varying thicknesses. Out of which three were made of loose leaves and seven were bound boards having either single or a combination of fibers with cornstarch and wood adhesives as binders. Scanning electron microscopy (SEM) analysis, thermal stability analysis and moisture content were carried out on date palm leaves to determine their fiber characteristics. It was observed that bound boards had high thermal conductivity as compared to the ones with loosefill whereas all the boards have good acoustic properties. It was concluded that the hybrid fiberboards can be used as sound as well as thermal insulation materials in the buildings.

Wimmers et al. (2019): Wimmers and his colleagues designed thermal insulation panels from wood shavings by employing filamentous fungi as a binder. Nine different species of wood-decaying fungi, five brown rot and five white rot, were utilized to degrade wood shavings from five different types of hardwood and softwood trees such as birch, aspen, spruce, pine and fir. The wood shavings acted as a substrate that provide nutrients to the fungi while fungi acted as a binding material due to the formation of a dense mass called mycelium by the decomposition of wood shavings. Petri dish trials were performed to obtain the most optimum growing conditions of fungi and Jar trials were carried out to determine the weight of wood shavings required to develop panels of thickness of 25mm approximately. A total of 13 specimen panels were prepared and most of them were fragile and brittle due to inadequate mycelial growth causing poor bonding between fungi and wood shaving. It was found that out of nine different fungi species, Polyporus Arcularius and Trametes Suaveolens (both dry rot) achieved the best growth whereas, in the case of trees, birch trees performed well. Thermal conductivities of both the panels were also found to be about 30% higher than the traditional insulation panels. Therefore, it was concluded that boards made from birch tree wood shavings in combination with Polyporus Arcularius or Trametes Suaveolens can be used as a replacement for the conventional insulation boards.

Beaudry and MacDougall (2019): Beaudry and MacDougall examined the performance of modular dry bale wall (DBW) panels when subjected to transverse and gravity loads. The DBW panel consisted of a timber frame, made from spruce-pine-fir flats and Canadian softwood plywood, covered on both sides with recycled wood sheathings to protect the straw bale infills. All the frame elements were assembled together with the help of screws. The straw bales were used in the form of blocks of size 460mm x 360mm x 840mm with a density of 90 kg/m^3. The DBW panels were analyzed for axial compressive and out-of-plane flexural strengths and the results obtained were then compared with the traditional stud walls. The utilization of DBW panels for residential construction was also assessed. The authors summarized that out of plane flexural strength and axial compressive strength were greater than stud walls by 168% and 11.2 % respectively.

Jami et al. (2019): In a work by Jami et al. (2019) various properties and construction applications of Hemp were reviewed. Hemp is a cannabis plant with fast growth rate and carbon sequestration properties. This study illustrated that hemp concrete is a lightweight material and has low thermal conductivity, good acoustic characteristics and fire resistance. However, it has a porous structure which is responsible for its hydrophilic nature and greatly influences its setting time. But its setting properties can be improved by using hydraulic binders such as lime, due to the generation of calcium silica hydrates (C-S-H) gel. They further explained that pre-fabricated panels or blocks of hemp concrete are most preferred in the construction of walls. It can also be used for insulation purposes in the exterior walls. It was summarized that hemp concrete exhibits remarkable environmental attributes due to carbon negative properties and hence, it can be characterized as a green construction material.

Suskiyatno et al. (2018): Suskiyatno et al. (2018) explored the manufacturing of wall panels utilizing waste paper and tapioca (cassava). Waste paper was treated to remove the toxic chemicals and dyes with the help of pouring. After releasing the trapped air and cavities by manual stamping, paper granules were then mixed well with tapioca. The paper bricks of size 50mm x 50mm x50 mm were then prepared and tested. It was found that paper bricks were susceptible to heat and rain therefore, a surface coating such as cement paste, cement-sand plaster or emulsion wall paints should be applied to it. They suggested that waste paper and tapioca can also be used with calcium cement or glass fiber reinforced concrete in the form of composite wall panels. At last, the authors stated that waste paper-tapioca composite panels can be used as an ecological building material in the form of wall panels.

CoDyre and Fam (2017): In this study, the axial compressive strength of sandwich panels with lengths varying from 500mm to 1500 mm was evaluated in order to utilize them as load-bearing walls for lightweight load applications. The skin of the panels was made from natural flax fibers as a replacement for conventional glass fibers. The core consisted of polyisocyanurate foam with three different densities 32,64 and 96 kg/m^3. They prepared 78 test specimens with different layers of flax fibers skins ranging from one to five. They determined that increasing the densities of foam core resulted in higher peak load however, there was a strength reduction with the increase in the length of samples due to global buckling for panels longer than 1250mm and local bucking for panels shorter than 750mm. It was also reported that panels with three skin layers of natural flax fibers exhibited similar axial strength as compared to panels with a single skin layer of glass fibers with a thickness equivalent to 85% of flax fiber skin. The compressive and tensile strains and lateral deflections in the specimens with flax fiber skin were substantially higher in comparison to specimens with glass fiber skins at identical ultimate loads.

Batouli and Zhu (2013): This research incorporated the application of Kenaf fibers as structural boards in the production of structural insulated panels that can be used for walls, partitions and flooring purposes. Kenaf fibers were used as an alternative for oriented strand boards to preserve the forest resources and reduce the embodied energy. A total of two panels were studied one with natural kenaf fibers and the other with synthetic glass fibers. LCA analysis from cradle to gate was also performed to compare the environmental impacts of both panels. The environmental impact was evaluated using impact categories such as global warming, water intake, acidification, natural resources depletion, indoor air quality, ozone depletion, etc based on Building for Environmental and Economic Sustainability (BEES). The results obtained clearly demonstrated that kenaf fiber-based structural insulated panels can considerably minimize the environmental impacts.

Numerous studies discussed in this paper were mainly focused on the three characteristics of waste material based wall panels: environmental impacts, insulation properties (such as thermal and acoustics) and mechanical properties (such as compressive and flexural strength). All the materials under consideration performed better as compared to the conventional construction materials on the structural as well as sustainability aspects. However, the behavior of wall panels under dynamic and cyclic loading conditions such as seismic forces and fatigue loading was not investigated. Since using waste materials as construction materials helps in reducing the construction cost, it supports the need for affordable housing. Recycling waste materials also facilitates the conservation of natural raw materials and thus, protects the deterioration of the environment. However, there is always a need for pre-treatment for the utilization of wastes as construction materials.

In addition to the proportion, the orientation and uneven/irregular distribution of fibers of various wastes also influence the properties of the wall panels. More importantly, the geographical scope or application of wall panels prepared from various wastes is found to be limited to specific weather or region instead of its suitability for different types of climates across the globe. For example, spruce bark fibers are available in temperate regions such as Europe or North America whereas date palm leaves are available only in regions having tropical and subtropical climates such as the Middle East or North Africa (POWO, 2022). Though the waste materials incorporated in the production of wall panels are natural and renewable making it an eco-friendly and healthy means of insulation but it requires a greater thickness to achieve the equivalent insulation properties as compared to conventional materials which would reduce the usable space of a room or unit. The organic vegetal fibers of wall panels are prone to fungal attack and might also act as nutrients for pests. After reviewing the available literature, it is evident that all the studies are focused on the insulation and mechanical properties and environmental sustainability, and no comprehensive study is conducted involving the fire resistance or flame retardancy of the waste material based wall panels.

The cotton fibers recycled by Sezgin et al. (2021) could impact the characteristics of composite wall panels depending upon the source whether it is obtained from production waste or from old used clothes. Also, utilizing polypropylene and polyethylene in the form of bottle caps, food, and cleaning containers in wall panels may release toxic fumes when exposed to high temperatures which may be a health hazard for the occupants. Wimmers et al. (2019) introduced the wood degrading fungi as a binding material in the development of insulation panels could be a unique approach but the fungal activity remains ambiguous throughout the process. In case of uncontrolled growth or if the fungi survived during the production process, it might lead to biological corrosion while use. The moisture content of fibers appears to be a key feature in assessing the performance of wall panels. Thus, it should be considered if the fibers of waste materials are naturally dried or oven dried. The axial compressive and flexural strengths are measured separately in all the considered studies. However, in real-life applications wall panels may be subjected to different types of loads simultaneously. Therefore, wall panels should be tested for various loads and combinations.

As stated earlier in the Introduction section, there are a number of government initiatives that encourage the adoption of cost effective and cleaner construction practices and the results of this paper can assist with meeting those schemes.

CONCLUSIONS

In this study, the research articles that focused on the development of prefabricated wall panels utilizing sustainable waste materials were reviewed and discussed. The structural performance in terms of parameters such as insulation characteristics (thermal and acoustics) and water resistance and sustainability aspects such as economic and environmental factors were also analyzed and compared to the conventional construction materials. Scientific evidences from the comprehensive literature review suggested that the application of sustainable waste materials in modular wall panels has the potential to promote affordability and minimize the environmental impacts of the construction industry. Conversely, there are also a number of limitations yet to be explored that impede its uptake such as transportation constraints, lack of skilled labor, high initial investment and unavailability of proper design guidelines.

Further research should be carried out to investigate the performance of waste-based wall panels in the following key areas:

- A full-scale level analysis should be conducted to determine its response when subjected to dynamic loadings such as earthquakes, and cyclones.
- A study should be performed to obtain the fire resistance or flame retardancy, acid resistance, and freeze and thaw resistance of panels.
- The durability of panels under extreme loading conditions such as fatigue loading should be evaluated.
- The long-term impact on the environment as well as the health of occupants should be properly assessed.

Based on the findings of this paper, it can be concluded that the use of waste materials in the development of prefabricated wall panels for their application in modular construction can help to move towards sustainability as deemed by the government policies. It can also serve as a remedial measure in construction waste disposal. Further, it could relieve the housing market in terms of rising prices and growing demand.

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