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Review

Promoting Circular Economy of the Building Industry by the Use of Straw Bales: A Review

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Abstract: Over the past decade, the concept of a circular economy has increasingly gained attention as a framework for guiding businesses and policymakers. Given its significant environmental impact, the building industry plays a pivotal role in the transition toward a circular economy. To address this, our review proposes a bio-based building material, specifically straw bale, which elaborates on the circularity of bio-based buildings based on the 3R principles of a circular economy: reduce, reuse, and recycle. In terms of the "reduce" principle, straw-bale buildings can reduce construction waste, the environmental impact, energy requirements, and carbon emissions. Regarding the "reuse" principle, straw-bale buildings utilize agricultural waste resources and are easily disassembled due to their prefabrication. As for the "recycle" principle, straw-bale buildings can undergo physical, biological, and biochemical conversion processes (thermochemical conversion), yielding both wooden composite boards and potential biogas and biomass fuels for electricity and heating. This study evaluates the contribution of straw packaging construction and the use of straw as a raw material, using the 3R principles to determine future research opportunities for the construction industry to achieve a circular economy. The results of this study offer circular economy solutions and interdisciplinary research insights for researchers and practitioners interested in the building environment.

Keywords: circular economy; construction industry; bio-based buildings; straw bales; 3R principles (reduce, reuse, recycle); sustainable development

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1. Introduction

The building industry is a highly active industry in both developed and developing countries [1]. Its practices wield significant influences on the sustainable development of society, the environment, the economy, etc. Additionally, the building industry stands as one of the primary sectors that consumes resources and generates waste within economic activities. It takes the lead as the top consumer of resources globally. The waste generated during construction-related production, operation and demolition is also a main factor in greenhouse gas emission, posing a challenge to the goal of achieving global peak carbon emissions [2]. Nowadays, the building industry still complies with the linear "procure–produce–process" economic model, which features a high consumption of natural resources and a low recycling ratio. The adoption of such a development model results in high waste production and poor sustainability as well as serious negative effects on the environment [3]. Thus, it is crucial to make efforts to boost efficiency in the use of construction resources for the global sustainable development of the building industry [4,5].

In recent years, attention toward the circular economy (CE) has significantly increased. Serving as an alternative to the traditional linear economic model, the CE holds the potential to offer a new solution for enhancing the sustainability of the building industry and is regarded as a novel approach to achieving its sustainable development [6,7]. The CE system returns materials and products to the supply chain as resources, with a focus on the decoupling of economic growth from environmental damage through the establishment of a regeneration system [8]. By maximizing the reuse and recycling of materials and components, the CE minimizes the primary resource consumption and waste production [9–11] while maintaining high efficiency and adding value to the products and materials [12,13]. The waste-to-resources model can effectively enhance the efficiency of the use of resources, and it is an important part in the closed-loop of the CE [14].

As depicted in Figure 1, the circular economy (CE) framework employs "reduce, reuse, and recycle (3R)" as guiding principles to establish a foundation for recycled waste management and the recycling of materials [8,15]. The first principle, "reduce", embraces the idea of "reducing from the source": minimizing the use of disposable resources, raw materials and waste from the source [16] while reducing or eliminating the production of pollutants [17], thus mitigating environmental damage [18]. "Reuse" refers to maximizing the utilization of products by maintaining and recycling them, extending their life span. Products or components that are not considered waste are reused and continue to function as before. Compared with the production of new products from raw materials, the concept of "reuse" may be an efficient alternative for managing waste because it can utilize resources more efficiently and significantly reduce environmental damage, i.e., the impact on the environment is minimal [19]. The principle of "recycle" proposes processing renewable materials into new products to minimize the consumption of raw materials.

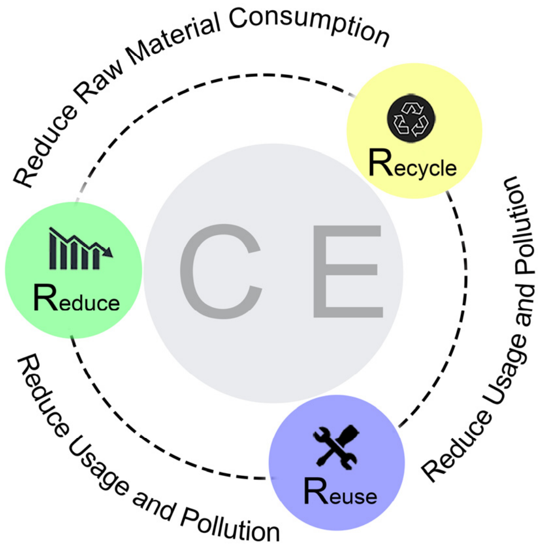

Figure 1. CE-3R model diagram.

The 3R principles have established the groundwork for global waste management and offer a solution for addressing global warming. The 3R principles have become a universally acknowledged concept embraced both in theory and in practical applications. However, recently, emphasis has been put on a more delicate tiered structure, with other choices for recycling such as "redesign", "renew", and "reuse". In this way, the maximum value of the resources can be preserved and reach a high level of circularity during the lifespan of multiple products [20]. Although the term "circular economy" may not have a universally agreed-upon definition, it generally encompasses the principles of reducing investment and reusing and recycling waste [15,21]. The CE model focuses on efficiently managing resources by minimizing consumption, and it substitutes the concept of "scrap" with the reuse, recycling, and renewal of materials and components [15,22].

The CE model has the potential to address the shortcomings of the linear economic model adopted by the building industry, resolving the tension between economic prosperity and environmental protection inherent in the linear economic model. However, the application of the CE concept remains at an early stage [22]. To sustain the cyclical nature of architecture engineering, it is of great importance to integrate the environmental and economic impacts of construction impacts into structural design. Relying solely on green construction during the operational phase is not enough to reduce its environmental effects [22]. A critical issue in this aspect is the selection of building materials, which urgently requires alternative developmental paths or the procurement of building materials from different sources [23]. Research has pointed out that one possible strategy to balance efficiency and to curb climate change is to choose low-energy building materials. Utilizing renewable materials and transitioning from a disposable linear economy to the CE are two approaches to addressing resource scarcity. From this perspective, natural materials stand out as favorable options due to their low energy requirements and minimal embedded energy [24]. However, traditional buildings carry significant carbon footprints and contribute to environmental degradation [25,26].

The inception of bio-based materials began in France in the 2000s, while the concept was formally introduced in a decree issued on 19 December 2012. The content and attribution conditions relating to the label "bio-based buildings" are in line with EU Regulation No. 305/2011. Thus, bio-based materials are defined as "materials produced by plant or animal biomass that can be used as raw materials for building and decorative products, fixed furniture and building materials in buildings". Bio-based construction products consist of cellulosic biomass, which is mainly made up of the material straw, which forms the bulk of the volume, and also contains binders (synthetic or mineral) and additives (organic or inorganic). The latter is added to improve the performance, thus enhancing the durability, efficiency, and performance of building materials. They have many uses, such as as flame retardants (FR), water repellents, and fungicides or fungicides. The use of additives must be in accordance with EU regulations such as the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation to avoid threatening human health or the environment.

Bio-based building materials appear to offer significant promise in advancing the sustainable development of the building industry. Firstly, buildings made of wood, straw, hemp or cork themselves have low environmental impacts. Bio-based materials, from their initial growth phase to their utilization, dismantling, and eventual recycling as building materials, form an entirely closed-loop system provided that the emissions related to the processes are disregarded [27]. Thus, the green construction technology represented by the use of bio-based materials, can contribute largely to the goal of lowering 50% of the global energy and materials consumption [28]. Secondly, with appropriate construction design, bio-based buildings' thermal capacity can match or even surpass the buildings using traditional petrochemicals as thermal materials [29]. Bio-based materials are also promising and effective building materials thanks to their carbon isolation effects, which can effectively reduce the carbon footprint of the construction industry [29].

This study explores the applicability of straw-bale building as a major bio-building type within the framework of the circular economy's 3R principles—reduce, reuse, recycle. By analyzing existing research on circular economy and bio-based construction, it aims to assess its feasibility and the potential of straw-bale building in promoting the circular economy, thereby offering an innovative approach to sustainable development.

2. Existing Research on the Circular Economy and Straw-Bale Buildings

2.1. Data Collection

For the literature reviews, we initially conducted a comprehensive literature examination across three domains, namely, the circular economy, its manifestations in the construction sector, and straw-bale construction. The Web of Science Core Collection's SCIE and SSCI databases were chosen for this research. While reviewing research on the circular economy, the term "circular economy" was used as the main search topic within the database, with the search duration set to "all" and the language filter for English. This yielded a total of 19,809 articles. In reviewing research on the manifestation of the circular economy in the construction sector, both "circular economy" and "construction" were used as search topics in the database. The search duration remained set to "all", with the language filter set for English, resulting in 1624 articles. Subsequently, in reviewing research on straw-bale construction, the term "straw-bale construction" was searched for, with the search duration once again set to "all" and the language filter for English. This yielded 2409 articles.

2.2. Bibliometric Visualization Analysis

Using the visualization analysis tool provided by Web of Science, research trends over the years for both the circular economy and its manifestation in construction were acquired. From Figure 2, it can be concluded that the development trend of the circular economy and its application within construction are in synchrony, ascending concurrently. This proves that circular economy implementation within the construction sector positively correlates with and significantly contributes to the advancement of the overall circular economy.

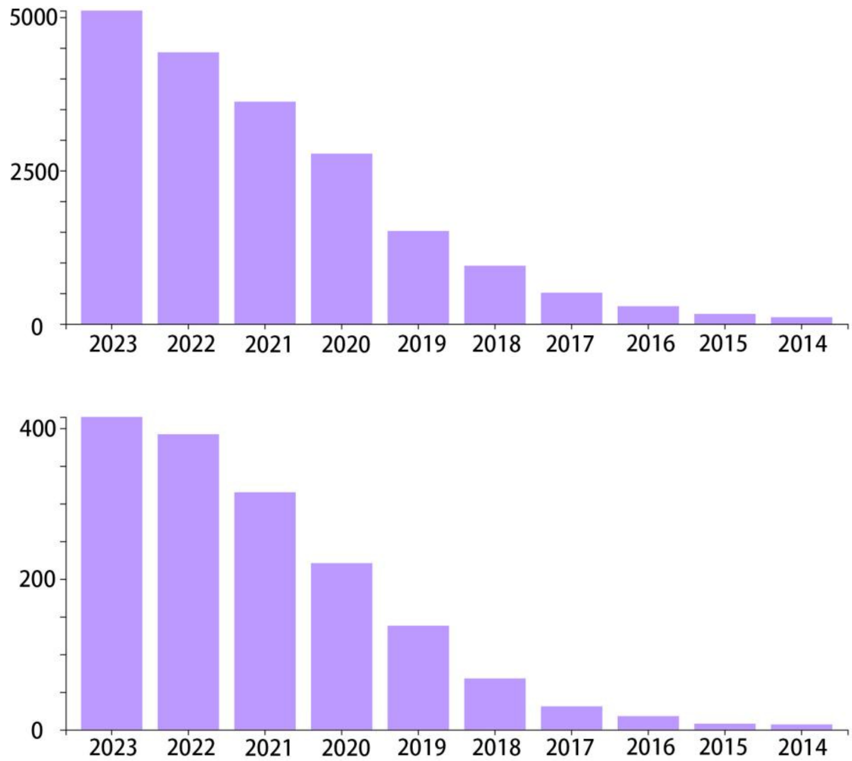

Figure 2. Annual publication trend of research articles on the circular economy (**above**) and its manifestation in the construction sector (**below**).

Using the Citespace tool, both sets of literature were subjected to visual analysis, encompassing keyword co-occurrence, clustering, and emergence to explore their content. As shown in Appendix A (Figures A1 and A2), the research found that the top ten keywords in the study of the circular economy in the construction field are "life cycle assessment", "management", "construction", "performance", "design", "energy", "system", "sustainability", "economy", and "waste" (Tables 1 and 2). The keywords "life cycle assessment" and "energy" highlight the importance of evaluating the environmental impacts and energy efficiency of construction materials such as straw bales. Straw-bale construction, which demonstrates a low energy consumption and high calorific value, becomes a viable, energy-efficient choice for the construction industry, aligning with the circular economy's focus on reducing energy use. Keywords including "management" and "system" emphasize the importance of structured approaches to recycling and resource management, indicating that systematic processes are crucial for enhancing sustainability in construction. The combination of "sustainability" and "waste" in research suggests an increasing trend of using agricultural residues such as straw for construction purposes, promoting the transformation of waste into valuable resources. Discussions in the construction industry about "economy" and "waste management" show a shift toward a circular economic model where materials are reused to minimize waste. The construction industry's interest in straw-bale buildings, as an effective waste management and resource recycling strategy, reflects its commitment to the principles of a circular economy. The significant presence of keywords related to post-treatment processes like "combustion" and "anaerobic digestion" in straw-bale building research indicates potential areas for cross-industry dialogue within the circular economy framework, focusing on the downstream impacts and energy potential of recycled materials.

As shown in Appendix A (Figures A3 and A4), the research found that the top ten keywords in the literature on straw-bale buildings are "wheat straw", "straw", "performance", "rice straw", "behavior", "biomass", "mechanical property", "pretreatment", "enzymatic hydrolysis", and "waste" (Tables 3 and 4). These keywords cover various important aspects of straw-bale construction, from the basic characteristics of the materials to the application of processing technologies. The keywords "mechanical property" and "performance" point to the research focus on the mechanical and functional assessment of construction materials such as straw bricks, ensuring that these natural materials meet the structural and durability requirements for building applications. The keywords "enzymatic hydrolysis" and "pretreatment" highlight the technological processes for the effective transformation of biomass materials, steps that are crucial for enhancing the usability and performance of the materials. "biomass" and "behavior" may relate to how biomass materials react and interact in different environments, which are essential for understanding how materials perform under various conditions. The keyword "waste" reflects a core concept in the circular economy; namely, how to convert discarded agricultural residues into useful building and energy materials, thus achieving waste reduction and efficient resource utilization.

Table 1. Top 20 keywords in the circular economy literature.

Keywords	Frequency	Centrality	Year
life cycle assessment	218	0.06	2016
management	179	0.05	2017
construction	169	0.12	2016
performance	160	0	2018
design	143	0.23	2015
energy	131	0.22	2007
system	124	0.01	2016
sustainability	123	0.13	2011
economy	113	0	2007
waste	112	0	2018
framework	93	0.14	2014
impact	93	0.02	2014
demolition waste	87	0.04	2019
model	85	0.07	2018
barrier	83	0	2010
waste management	80	0.03	2018
concrete	78	0	2015
strategy	72	0.04	2018
built environment	71	0.01	2017
building material	70	0.02	2015

Table 2. Keyword clusters in the circular economy literature.

Number	Category
0	urban mining
1	circular economy
2	barriers
3	metabolic engineering
4	construction and demolition waste
5	carbon dioxide
6	industrial symbiosis
7	solid waste management
8	circular supply chain
9	renewable energy
10	smart city
11	urban agriculture
12	industry 4

Table 3. Top 20 keywords in the straw building literature.

Keywords	Frequency	Centrality	Year
wheat straw	313	0.15	1991
straw	243	0.1	1991
performance	171	0.03	2002
rice straw	168	0.15	2003
behavior	159	0.33	1992
biomass	150	0.38	1991
mechanical property	141	0.04	2008
pretreatment	86	0.23	2002
enzymatic hydrolysis	86	0.02	2004
waste	85	0.03	2002
lignocellulosic biomass	82	0	2013
soil	78	0.07	1995
concrete	78	0.05	2013
fiber	78	0.04	2000
wood	70	0.06	2001
carbon	69	0.23	1994
nitrogen	69	0.03	1991
energy	69	0.03	2007
impact	69	0	2012
lignin	66	0.09	1993

Table 4. Keyword clusters in the straw building literature.

Number	Category
0	thermal conductivity
1	organic matter
2	nest building
3	wheat straw
4	agricultural residues
5	solid convectivity
6	enzymatic hydrolysis
7	steam explosion
8	tandem mass
9	compressive strength
10	hemp concrete
11	anaerobic digestion
12	combustion

Based on the keywords and focal areas of the two research domains, it is evident that straw-bale buildings play a crucial role in achieving a circular economy in the construction field. Therefore, straw-bale buildings hold feasibility in realizing the circular economy in the construction field, showcasing considerable adaptability in certain aspects. Utilizing bio-based materials and agricultural residues to produce straw bricks can achieve resource recycling while offering energy-saving, low-carbon, and eco-friendly construction material options.

3. Achieving the "Reduce" Principle of the Circular Economy

The building industry stands as one of the foremost contributors to global waste generation, consuming vast quantities of natural resources and generating significant waste during construction and demolition processes. Thus, in order to minimize or eliminate this waste, advancements in technologies and methodologies are imperative [30]. Most of the construction activities still rely on labor-intensive on-site building methods, which, due to their high pollution levels, do not comply with sustainable development objectives. Moreover, these methods often lack stringent quality control due to site-specific conditions. Such activities also contribute to a lot of construction waste, which constitutes a significant challenge in waste management and disposal [31]. Meanwhile, building energy consumption is projected to rise steadily as a result of the increasing population and people's increasing demand for household appliances and indoor comfort [5]. Thus, the evaluation in the current study of buildings' energy consumption is of vital importance [32]. The focus on green construction, alongside its energy conservation implications has drawn more and more attention worldwide [33].

3.1. Reducing Construction Waste and the Environmental Impact

Bio-based fibers possess numerous advantageous properties, with straw being a notable example due to its renewability, biodegradability, and environmentally friendly production process [34]. Straw is a major bio-based chemical fiber derived from nature, and it is used as a building material after processing [35]. The method of deconstructing waste at the end of a building material's life cycle is very important. Figure 3 demonstrates how the prefabrication of bio-based materials in the construction process can diminish construction waste and the environmental impact. Straw naturally degrades in the soil and participates in the natural system, and thus no construction waste is produced. Moreover, finely crushed straw significantly shortens the broken length and increases the contact area of straw stems with the external environment, thereby accelerating the decomposition rate of the straw [36]. Straw residues are potential sources of organic carbon and plant nutrients to improve soil organic matter dynamics, nutrient cycling, and the soil's physical environment. Compared with burning, cutting the straw and sending it back to the fields directly can avoid environmental pollution [37]. Meanwhile, all nutrients contained in the straw can be sent back to the soil in this way. Thus, the utility of the soil organic carbon and nutrients is promoted and the physical, chemical, and biological characteristics [38–40] of the soil are improved, facilitating nutrient recycling, averting nitrogen loss, and strengthening the soil's structure [41,42]. The cut straw can provide significant nutrients to increase crops' productivity as well.

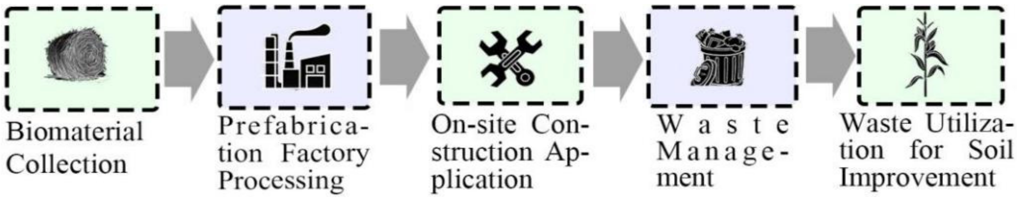

Figure 3. Prefabrication of bio-based materials in the construction process.

Meanwhile, the prefabrication of straw-bale buildings also plays a crucial role in determining the incidence of waste. With a prefabricated low-carbon modular construction system and the "design for disassembly" principle, straw-bale buildings stand the chance of avoiding waste and reducing greenhouse gas emissions [43]. The building type is built in a temporary "flying factory" near the construction site, mostly using local labor and straw. This process, besides reducing the waste produced during the pre-cutting of engineered timber, can utilize most of the materials with near-zero processing waste [44]. Recent research analyzed the impacts of the greenhouse gas produced in the buildings' life cycles and the life cycle of the prefabricated modular straw buildings by using the "cradle to demolishment" and "cradle to the grave" approaches [45,46]. The modular buildings perform better than conventional buildings, especially in their potential in decelerating global warming. Through the prefabrication mode, straw-bale buildings made in the planning and designing stages have reduced more waste in the construction sector than in on-site construction practice [47]. Furthermore, standardization, modularization, and prefabrication methods contribute to cost reduction in building construction. Compared with traditional construction methods, on-site prefabricated construction significantly minimizes construction waste, waste water, noise, toxic gases, and dust [48]. The potential for achieving zero-waste production through the recycling of prefabricated straw-bale buildings exemplifies the principle of green construction. It emphasizes waste reduction and building flexibility in the construction sector and thus mitigates the environmental impacts associated with building and demolition activities, which aligns closely with the concept of a circular economy (CE) [35,49].

3.2. Reducing the Energy Requirement

The embodied energy of bio-based materials are notably lower than that of fossil-based materials [50]. Therefore, recycling rich and renewable local biological resources in construction can significantly reduce energy consumption in the industry. Globally, industries are increasingly turning to manufacturing processes as they consume approximately 13% less energy than the electrical energy consumed in on-site construction. Meanwhile, the manufacturing processes of prefabricated construction consume around 28% less fuel than those of on-site construction [51].

As the main source of bio-based building materials, agricultural residues such as wheat, corn, and rice straw have long been utilized in building insulation due to their hollow structures, low cost, low density and thermal conductivity [5]. The thermal conductivity of ecological materials falls within a range of 0.035 to 0.051 W/(m.K), which is similar to that of traditional insulation materials (0.030 and 0.042 W/(m.K)) [52]. Compared with the system of conventional buildings, straw-bale buildings are cost-effective and achieve high thermal performance [53]. This allows them enhance the thermal capacity of the buildings, improving insulation performance, reducing heat loss, and preventing overheating in summer [54].

Using straw bales as thermal insulation material not only saves energy [5] but also lowers the buildings' heating energy consumption and greatly reduces the need for heating and air conditioning, ensuring occupants' comfort [55]. Therefore, straw-bale buildings are commonly deemed suitable for regions with high heating needs. Wall et al. (2012) demonstrated through testing that prefabricated innovative low-carbon building prototypes using straw-bale plates exhibit excellent thermal performance [44].

The UK's Low Impact Affordable Communities for Living (LILAC) project highlights the benefits of using straw bales to improve the thermal envelope of buildings, resulting in reduced operational energy consumption. The project shows that typical apartments have a thermal energy usage of 35.73 kWh/m^2/year. By employing the ModCell straw-bale wall system, the energy efficiency ratio is 25% higher than that of the buildings built in accordance with the 2010 Building Code. This improvement is particularly advantageous given the average space heating demand of 140 kWh/m^2/year for existing housing stocks in the UK [56]. Furthermore, Yin et al. (2020) proposed an evaluation of energy sustainability of the buildings with straw-bale walls in China's rural areas, and the results showed that applying such structures can lower thermal consumption by 45.82–204.07 kWh/m^2/year and reduce coal consumption by over 40% (Figure 4) [37].

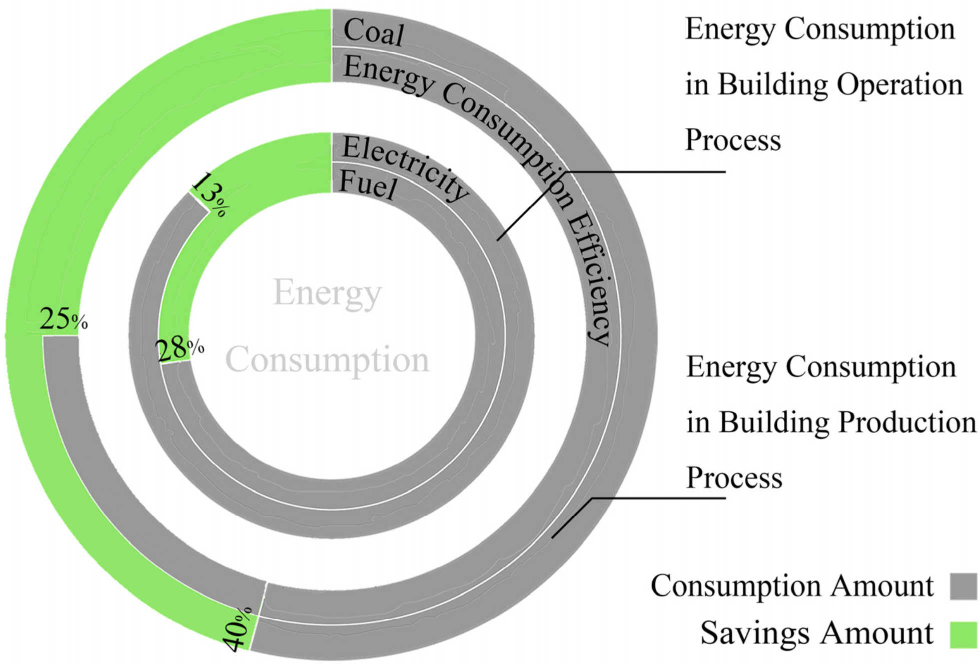

Figure 4. Energy consumption in building production process.

3.3. Reducing Carbon Emissions

Conventional construction materials including steel and cement have a significant impact on the environment. Cement, in particular, is a crucial building material but also contributes to approximately 5% of total man-made carbon dioxide emissions. This makes the cement industry a key sector for decelerating the emission of carbon dioxide [57]. With the increasing demand to reduce carbon emissions in the building industry, there is a growing need for low-embodied-carbon buildings. Globally, numerous initiatives are underway to reduce the carbon footprint of the building industry. Using bio-based building materials including straw bales can be an efficient method to achieve a low carbon footprint for buildings [58]. Compared with concrete and other conventional building materials, straw bales are fully renewable and sequester carbon throughout their life cycle, effectively locking carbon within the plant-based building materials [32,59]. The proper treatment of bio-carbon storage is critical to quantifying greenhouse gas emissions from bio-based materials. Additionally, the production of bio-based materials results in lower carbon emissions and embodied energy compared with that of petrochemical materials [60]. The use of straw bales can greatly reduce carbon emissions and embodied energy compared with conventional materials, including fired brick and cement blocks [61].

Recently, scholars have researched the refinement of bio-based building materials, including straw bales [62]. Based on the research, quick-growing bio-materials show greater potential as carbon sinks due to their shorter rotation period, offering a greater capacity for carbon sequestration (Figure 5) [63]. Crop cycles of wheat and rice span less than a year, making them promising bio-based building materials. Wheat straw bales often absorb around 1.35 kg of carbon dioxide per kg of body weight [64]. According to the GWPbio figures, each kind of raw material and biological carbon repository can be used to quantify the effects of the carbon cycle [65]. Yin et al. suggested expanding the use of straw bales in future architectural designs in Northern China. They advocate incorporating straw bales into mainstream mid-rise structures to lower embodied carbon and operational carbon as well as to eliminate major pollution sources [53].

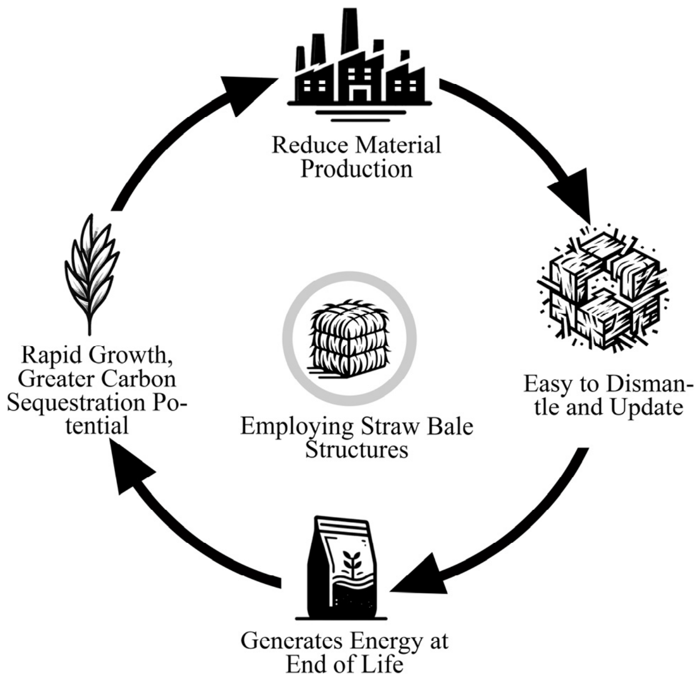

Figure 5. Carbon-reduction process for straw bales.

To understand the impact of biological carbon storage on climate change, researchers have evaluated the entire life cycle of products [66], including the initial stage (production, transportation to the construction site, and construction), the usage stage (maintenance, repair, and energy loss during transmission), and finally, the end of life (EOL) stage (demolishment, transportation, and EOL processing) [60]. Boyd et al. estimates that recycling and renewing can significantly reduce greenhouse gas emissions by over 50% compared with emissions from demolition alone, thus aiding the mitigation of global warming [67]. In addition, recycling replaces the preliminary production of new products and relieves the EOL burden on deserted buildings. Recycled materials can be reused in new buildings, building repairs, or renovation, thereby averting energy consumption and greenhouse gas emissions throughout the entire process from the raw material extraction to the final production. Cornaro et al. conducted an comparative life-cycle assessment of straw-bale walls and conventional fired-brick walls with the same thermal conductivity in the experimental building. The results indicate that during the production and construction stages, the equivalent carbon dioxide emissions and the embodied energy of the straw wall are 50% lower than those of the traditional wall [68].

Therefore, using straw-bale structures to replace conventional building envelopes serves a dual purpose: storing carbon and making contributions to global carbon-reduction targets by lowering carbon dioxide emissions. This occurs during both the construction stage and the demolition stage. Figure 5 illustrates the entire carbon-reduction process associated with straw-bale construction. Considering the carbon-sequestration function of bio-based materials comprehensively, the initial construction emits zero carbon. It is proved that the benefits of the carbon dioxide contained in bio-materials has the potential to significantly decelerate global warming. If these bio-materials are used to generate energy at the end of their life, carbon emissions can be further reduced [69]. In summary, compared with traditional construction materials, the use of bio-based building materials has significant potential to reduce carbon dioxide emissions in the building industry. Straw bales, as a kind of bio-based building material, have a notable advantage in carbon sequestration throughout the building life cycle compared with traditional materials. This advantage will lower the carbon footprint associated with the building industry. Additionally, this type of bio-based material plays a positive role in enhancing the soil quality and increasing crop yields as well. Therefore, the promotion of bio-based building materials such as straw bales will have a positive impact in mitigating global warming. It can help the construction industry achieve low-carbon goals and promote the effective use of agricultural waste at the same time. Moreover, the end-of-life conversion of bio-based building materials into energy could further reduce carbon emissions, underscoring the vital role of the circular economy and green building in achieving environmental sustainability.

4. Achieving the "Reuse" Principle of the Circular Economy

Biomass derived from agricultural waste is abundant on Earth. Agricultural waste, including wheat straw and straw, are often either used for animal feed or burned in the fields, which not only adds negative economic value [70] but also contributes to serious air pollution [71]. Addressing this issue demands environmentally friendly disposal solutions for straw rather than the current practice of field burning. Embracing sustainable approaches to utilizing crop stubble can notably mitigate air pollution arising from open burning [72]. Some countries have implemented agricultural production policies to prohibit the burning of primary resources in situ. Therefore, agricultural residues have become abundant, requiring new markets and appropriate applications. To meet the reuse principle of CE, straw-bale buildings offer a dual benefit: the reuse of agricultural byproducts and the ability to be disassembled through prefabrication.

4.1. Reuse of Agricultural Waste Resources

As a kind of solid waste, straw used in building materials has been widely discussed for reuse worldwide. Straw, being one of the most abundant lignocellulosic agricultural residues globally, represents a crucial natural resource. In China, for instance, the substantial amount of recycled straw residue in the field and the portion that can be collected and utilized by direct repair amount to approximately 616,000 tons, accounting for about three-quarters of the total straw production [73]. This serves as a powerful driving force for expanding the use of straw in the building industry. Agricultural straw, due to its hollow structure, low thermal conductivity, low density, and low cost [74], is considered to be a better building material compared with conventional construction materials. The use of straw bales in the building industry will facilitate the disposal of straw and will provide an energy-efficient alternative to current building types. Straw bales, typically sourced from wheat, oats, or other types of straw, are utilized to create building envelopes. The UK Lilac Garden community adopted straw and wood as a source of materials for bio-based buildings due to their suitability for community-built elements and their potential to bolster local supply chains. In the UK alone, 2.37 million tonnes of waste straw are returned into farmland annually, enabling 423,000 houses to be built [56], underscoring the significant potential for straw reuse in the building industry.

Platt et al. investigated the novel production of oriented prototype straw bales with the specific objective of their application in the construction sector [75]. Their innovative approach involves repurposing straw originally sourced from agricultural bales (Figure 6). The reconfiguration of the baling process is aimed at orienting the straw fibers in a preferential manner to substantially enhance both thermal resistance and mechanical performance. In this process, the loose straw is manually loaded into a compaction chamber and subsequently compressed utilizing a hydraulic jack. This re-baling process yields significant improvements in thermal resistance, with a reduction of approximately 28% in the required insulation thickness.

Figure 6. Production of oriented prototype straw bales.

Therefore, bio-based architecture stands out for its utilization of abundant available agricultural waste resources that are all derived from recycled products, thereby fostering a circular economy. Leveraging agricultural waste as an alternative to conventional building materials and integrating recycling into production processes can significantly mitigate environmental impacts. This approach represents a prime CE strategy for reducing environmental impacts while adding more value to the product [76].

4.2. Ability to Disassemble Achieved by Prefabrication

The average composition of building demolition waste in Europe shows that up to 85% of waste is stone waste [77], such as end-of-life (EOL) concrete. At present, the recycling of waste mainly focuses on scrap metal and steel products with higher value added. Most of the waste is exposed to the open air or deposited in landfills without any treatment, which not only leads to substantial waste removal expenses but also occupies land, and the accumulation of untreated waste poses a significant risk of environmental pollution.

Recent prefabrication innovations have revolutionized the new building industry, accelerating the prefabrication of buildings. Prefabrication of frames, in particular, is gaining traction as a viable alternative to traditional demolition and recycling methods [78]. Prefabricated straw-bale buildings adopt the general project contracting mode, which firstly optimizes the architectural design and material selection and assembly based on the technical characteristics of straw-bale buildings. This system includes the design of basic living units that can be superficially grown, the design of invisible variable nodes that are convenient for disassembly and assembly, and the architectural responsibility system based on the general contract management mode of EPC projects. It is often suggested that deconstruction, demolition design, and reuse design need to be incorporated into the design phase, which is crucial for reducing the generation of construction waste [30]. To get rid of landfills, products should prioritize their reconfigurability and detachability, making them easy to dismantle or recycle during their usage stage.

As shown in Figure 7, the prefabrication of straw-bale buildings has defined the organization of routine procedures and operating procedures [79], making the disassembly and deconstruction of building structures more convenient. This approach promotes the design of the life cycle and ensures the material uniformity of buildings with extensive service lives [79]. The premise of deconstruction lies in the design of prefabricated, preassembled, and modular structures and the simplification and standardization of connecting details, along with designs that accommodate deconstructed logistics, the reuse of materials and the realization of a closed-loop cycle building materials [80]. Due to efficient manufacturing, prefabricated timber structure construction activities reduce wood waste to almost zero [81], thus making it easier to reuse and recycle building components and materials after the end of the structure's life [31,82]. Overall, prefabricated bio-based building materials are easy to be recycled in two aspects. Firstly, waste minimization during the design phase involves the design of structures and goods with an extended service life, making them easy to repair, upgrade, or use in different ways in future cycles. This approach is supplemented by avoiding errors and by guiding construction activities while taking into account waste minimization [3]. Secondly, the prefabrication of bio-based buildings adopts the off-site construction mode, which helps to reduce the wasting of resources and which makes it possible to disassemble and reuse building components in other places. There are four main scenarios for the reuse of bio-based building materials after deconstruction, such as (1) the relocation of buildings; (2) the reuse of components; (3) the reprocessing of materials; and (4) the recycling of materials. Of the four cases, reuse is preferred over reprocessing or recycling because it requires no additional energy, whereas reprocessing or recycling involves degradation and a limited contribution to new products. Through prefabrication and a modular design, bio-based building materials can achieve higher resource efficiency and environmental friendliness throughout the building life cycle. Prefabrication not only reduces material waste during construction but also simplifies the process of material recovery and reuse during the demolition phase. This approach not only enhances the overall sustainability of building materials but also provides the construction industry with a practical pathway to transition toward a circular economy. By optimizing design and construction processes, material utilization can be significantly improved, reducing the environmental impact.

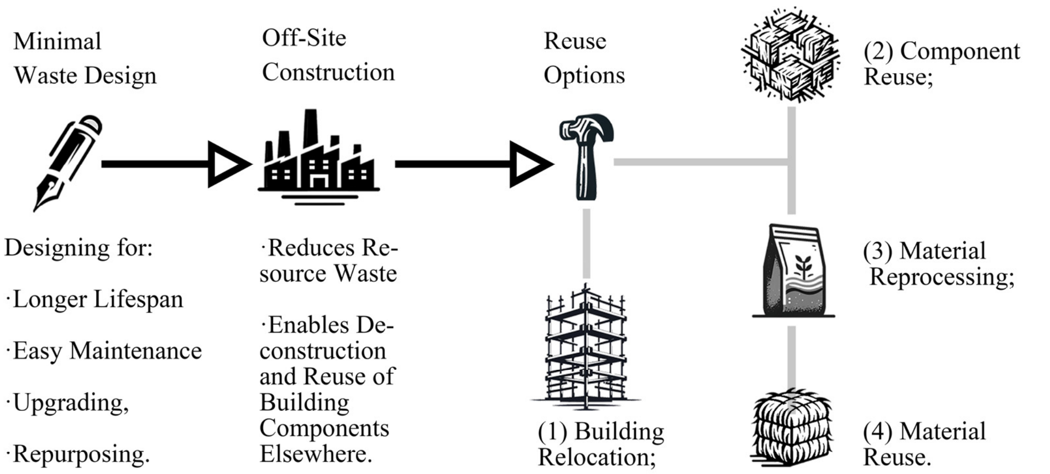

Figure 7. Advantages of prefabrication in straw-bale buildings.

In addition to the process, the most common way to recycle concrete from traditional buildings is to simply break it and then use it as a foundation for road construction, which is considered to be a low-grade or low-value-added route. For high-grade concrete recycling, the wet process is typically utilized. However, this method necessitates large washing equipment, which can be prohibitively expensive [83], so the recycling of ordinary (normal weight) concrete waste is not yet popular in the EU. Conversely, prefabricated straw-bale buildings are based on modular products which are constructed off-site. Compared with reinforced concrete, they can be easily dismantled for reuse or used as energy sources at the end of the building life span.

Shea et al. introduced the ModCell prefabricated straw-bale panel system [84]. This innovative panel is assembled by using straw bales to fill a supporting framework measuring a dimension of 3.19 m in width, 2.66 m in height, and 0.49 m in thickness (Figure 8). Typically, the framework is made from engineered glue- or cross-laminated timber. The internal arrangement of straw bales adheres to a traditional brick-wall masonry pattern, with alternating stacking and secure fastening accomplished using timber dowels. Additionally, stainless steel reinforcements are incorporated as corner braces and vertical strapping is used to reinforce the structure. Both faces of these panels are meticulously coated with lime render in three layers. Notably, this panel system has demonstrated its practicality and effectiveness through its successful implementation in the construction of a prototype building located at the University of Bath, known as the BaleHaus at Bath.

Figure 8. ModCell panel (**left**) and the complete prototype house at the University of Bath campus (**right**).

5. Achieving the "Recycle" Principle of the Circular Economy

Solid-waste management is a challenge for urban authorities in developing countries. The main reason is that the increased waste production has burdened municipal budgets with high management costs. Thus, using sustainable technologies to decelerate climate change and to provide continuous energy is vital for realizing a CE [85]. As the fourth-largest energy source in the world, biomass can be transformed into new energy products like electric power, molded fuel, methane, liquid fuel, etc., which is rather important not only for tackling global climate change and the contradiction between power supply and demand but also for ecological and environmental protection [86]. Crops used as bio-based construction materials, such as agricultural and forestry residues, can be recycled and re-enter the circulatory system after reprocessing. This transmission be achieved in three major ways: physical treatment, involving the use of grass clippings as pressure plates; biochemical (physical) treatment, which involves gas by fermentation; and (thermal) chemical treatment, which provides energy for heat, steam, electricity and biological fuel by methods like direct combustion [87–89].

5.1. Recycling through Physical Treatment Processes

Wood waste such as wooden floors, ceilings, and ornaments from construction and demolition sites accounts for 10% of the total amount of waste, surpassing only concrete waste. The wood waste generated in construction and demolition sites is usually not included in any recycling list and ends up in combustion facilities or landfills [90]. In the face of worldwide shortages of forest resources, there is growing interest in producing particleboards with agricultural residues [91]. Wood has always been the main source of raw materials for particleboards and fiberboards, while wood biomass is the most traditionally used raw material in the lignocellulosic biocomposite industry [92]. The topic of how to recycle construction wood residues into useful products has been studied for decades [93], and the most common method of reusing them is to manufacture particleboards from wood waste recycled from construction.

Yet recently, rice–wheat straw (RWS) has drawn more attention from researchers. Wheat straw contains large amounts of fiber. Particleboards with densities ranging from 0.59 to 0.8 g/cm^3 are named medium-density particleboards. Straw particleboards, due to their rigidity, strength, and low cost, are applied widely [94] and have the potential to replace wood in particleboard manufacturing [95]. Therefore, it is possible to use straw brick-wall envelopes as raw materials for making particleboards, which will alleviate the huge demand for wood. By grinding the recycled straw bales into fibrous particles [96] and using phenolic resin as the adhesive, it is possible to produce polymer composite particleboards [97] with low formaldehyde content [98].

Among many products, the recommended properties of wood particle composite boards are that they are able to absorb noise, maintain the temperature of the indoor living space, and partially or completely substitute for timber particleboards and heat shields [99]. The straw–wood particle composite boards adopt the approach taken in the man-made board sector to produce insulation boards. Agricultural lignocellulose fibers such as rice and wheat straw can easily break into fragments or granules, similar to wood particles or fibers (Figure 9). Straw is also chosen as a raw material because of its usability [99]. We can use straw–wood particle composite materials both as insulation materials and as insulation boards. Insulation boards can be used for a variety of purposes, including for roof and wall sheathing, subfloors, the interior surfaces of walls, and ceilings.

(**a**) (**b**)

Figure 9. (**a**) Solid-wood particle board; (**b**) and straw–wood particle board.

5.2. Recycling through Physical Biological Processes

Biological energy is the main domestic energy for rural families in developing countries, because it is cheap and readily available. Using biological energy productively is a major strategy not only for rural families to raise their salaries but also for improving their health, living environment, etc. [100]. Wheat straw waste used in bio-based buildings has great potential for anaerobic digestion [101], which, if transformed appropriately and biologically into methane, can be a potential source of energy [101,102].

The anaerobic biological treatment of agricultural solid waste has become more and more important in recent years. As shown in Figure 10, the technology to transform agricultural biomass waste into bioenergy is environmentally friendly and sustainable. Anaerobic digestion, a biological process facilitated by various types of microbes, decomposes biomass waste into energy. The process occurs in an anaerobic environment, utilizing macrobes that can decompose organic ingredients into biogas to produce methane [103]. How much methane can be produced during the anaerobic digestion of biodegradable organic matter depends on the amount and type of material added to the system [101]. After being preprocessed at 180 °C, wheat straw produces 53% more biogas [104], which can be used to power EDM or turbines.

In addition, there is a growing interest in transforming manure-crop residue mixtures into methane for its clear benefits. Firstly, when crop residues are mixed with manure, more methane can be generated, as the annual amount of corn stalks and wheat straw is about four times that of manure [105]. Secondly, such a mixture can improve the nutritional compatibility of high-nitrogen fertilizers and produce crop residues with high carbon content but deficient in nitrogen. Research indicated that mixing pig manure and corn stalks can generate fertilizers. Methane yields from manure–straw mixtures are significantly higher than those from pig manure or straw alone, which is attributed to a more favorable carbon–oxygen ratio [106,107]. Adding straw to pig manure enhances the biogas yield in thermophilic anaerobic digestion, with over 50% of the carbon in straw converted into gas. Moreover, bio-based products deprived of additives can be recycled or reused for composting or biodegradation. They can also be transformed into energy or sent to landfills. Unlike polyurethanes, straw can be composted simply after selective deconstruction. The composition or chemical properties of carbohydrates (such as lignin, cellulose, hemicellulose content) and the density of other nutrients they contain are related to all sorts of domestic and industrial applications [73].

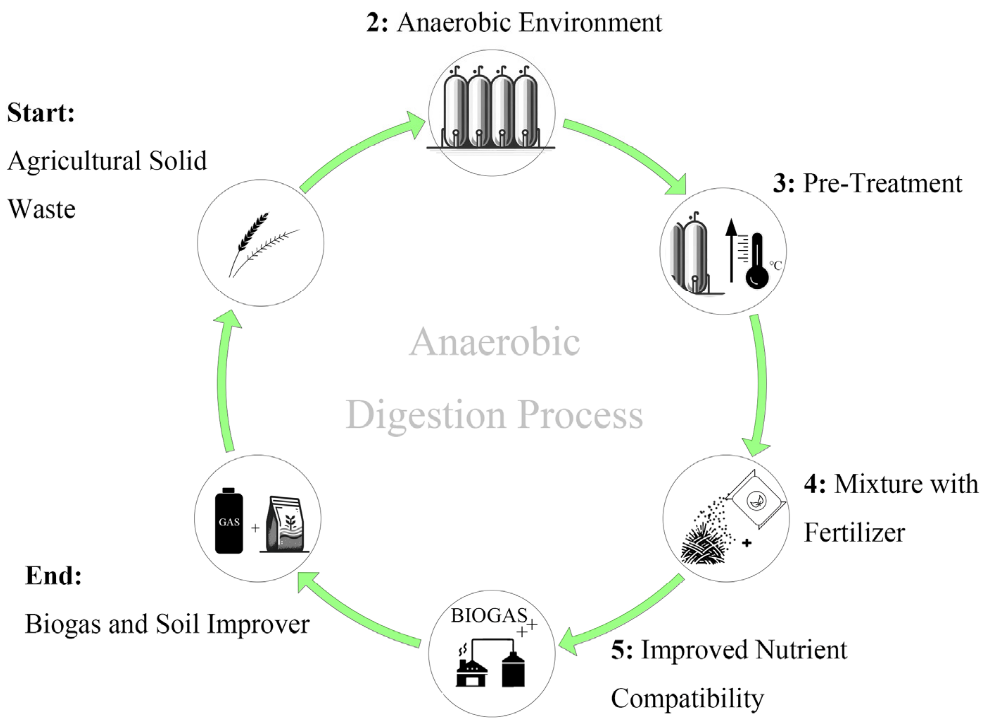

Figure 10. Anaerobic digestion process.

5.3. Recycling through Biochemical Conversion (Thermochemical Conversion)

Rising energy prices and environmental demands have rekindled people's interest in harnessing crop residues for energy production. Biomass energy is the richest and most versatile renewable energy in the world [108], with the potential to significantly contribute to the renewable energy supply by producing useful and valuable bio-fuels [109]. Crop residues such as grain and corn stalk residues can be transformed into liquid or gaseous bio-fuels through thermochemical or biotechnological processes, representing a promising resource for bio-energy development [110]. Transforming agricultural residues into biomass feedstocks for power generation and district heating is becoming increasingly common [111], particularly in rural areas of developing countries [112], where the potential of crop residues for bio-energy is gaining more and more attention [113].

Straw stubble used in bio-based buildings, such as cellulose and lignin, contains large amounts of biochemical energy. This kind of biomass can be partly acquired in a sustainable way. If combusted at the end of its service life, it can be converted into bioenergy generating heat and/or electricity [87] to offset the consumption of fossil fuels [114], effectively recycling its energy [115]. Pulverized biomass fuels burn much faster than coal and can produce flames similar to oil or gas fuels, delivering the same high-power output [116]. Due to the more efficient processing and combustion, the energy cost in upgrading is fully compensated. As with the energy balance, production costs are recovered from combustion, ensuring a balanced energy budget. Additionally, a higher combustion efficiency can also lower the consumption of fuels [116].

Meanwhile, different residues from crop production hold potential for meeting renewable energy targets. Applying biomass to transporting fuels can increase the use of heat and electricity production significantly [117]. Specific regulations on how to improve and ensure the productive utilization of bioenergy are also needed [100]. The new emerging concept of integrated waste bio-refinery fosters the circular bio-economy and addresses current waste issues [52]. It involves the integration of several biochemical or thermochemical transformations to produce value-added products, essential for achieving a circular economy in developing countries [118]. Rabbat et al. [52] proposed a waste management strategy pertaining to bio-based building products that focuses on waste-to-energy (WTE) routes. In cases of non-recyclable wastes, this strategy diverges from traditional landfill disposal methods. Instead, it entails the conversion of bio-based construction waste into thermal energy, electricity, and alternative fuels to cater to market demands, yielding substantial financial gains. It is projected to mitigate around 315,000 tons of CO_2 emissions and conserve 75,000 tons of fossil fuels per tonnage of waste valorized, amounting to an estimated economic benefit of 78.9 million euros. Furthermore, the recovered energy can be seamlessly integrated into an integrated biorefinery system, allowing for the production of value-added products such as bioenergy, biochemicals, and biofuels. Consequently, this comprehensive strategy not only contributes significantly to environmental preservation but also generates substantial economic profits.

As the global demand for sustainable buildings grows, it is expected that more projects will adopt bio-based materials in the future. These materials not only help reduce construction waste and carbon emissions but also significantly enhance the overall environmental performance of buildings through their recyclability and reusability features. Moving forward, policymakers and the construction industry should focus more on integrating circular economy principles into building design and construction. This may include promoting the use of environmentally friendly building materials through legislation and regulations, as well as supporting the research and development of new material technologies to enhance efficiency and sustainability. Additionally, public awareness and consumer demand for eco-friendly buildings will continue to drive the market toward these solutions. Therefore, the construction industry is likely to undergo a significant transformation by using bio-based materials and circular economy approaches, addressing environmental issues while also driving technological innovation and economic growth.

6. Conclusions

In conclusion, this review proposes a bio-based building material solution that elaborates the circularity of straw-bale buildings from the basic dimensions of the 3R principles of the circular economy. It evaluates the contribution of straw-bale buildings and the use of straw as a raw material within the context of CE principles, identifying future research opportunities for achieving a circular economy in the building industry.

The research underscores several environmental benefits of the transition from bio-based buildings to a circular built environment:

"Reduce" principles: (1) Reduce the construction waste and environmental impact; (2) Lower the energy requirement; (3) Minimize carbon emissions;

"Reuse" principles: (1) Reuse agricultural waste resources; (2) Enable disassembly through prefabrication;

"Recycle" principles: (1) Utilize physical treatment processes for recycling; (2) Employ biological processes for recycling; (3) Explore biochemical conversion (thermochemical conversion) for recycling. This approach can not only facilitate the production of wooden composite boards but also offers the potential for converting waste into biogas and biomass fuels for electricity and heating purposes.

Properly transforming and utilizing straw in straw-bale construction can effectively reduce the pollution caused by straw burning while also providing additional policy compensation to villagers. The results of this study offer valuable insights into circular economy solutions and interdisciplinary research for the building industry, serving as a resource for both researchers and practitioners interested in the CE and the building environment. This study utilizes years of experience gained in policies and industry and explores how to fully utilize bio-based buildings from a CE perspective, which may be the key to achieving a circular building industry.

An important aspect of future work is to make necessary adjustments to the current building design standards in order to incorporate them into the circular strategy of this study. In addition, future research may explore in more detail the connection between circular construction technology and social challenges in order to find more scientifically reasonable solutions. For example, material costs are integral to overall construction expenses and can influence the selection of bio-based building materials. Even though bio-based buildings have a better CO_2 balance, in most cases, they are not necessarily a cost-effective option for reducing emissions in the long run. For this reason, a more detailed cost analysis should be done before policymakers begin to design and promote policies on bio-based buildings. Establishing cost-effective solutions could significantly enhance the closed loop of these emerging materials and bolster the circularity of the built environment.

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Data Availability Statement: No new datasets were created or analyzed during this study. Data sharing is not applicable to this article as no datasets were generated or analyzed.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

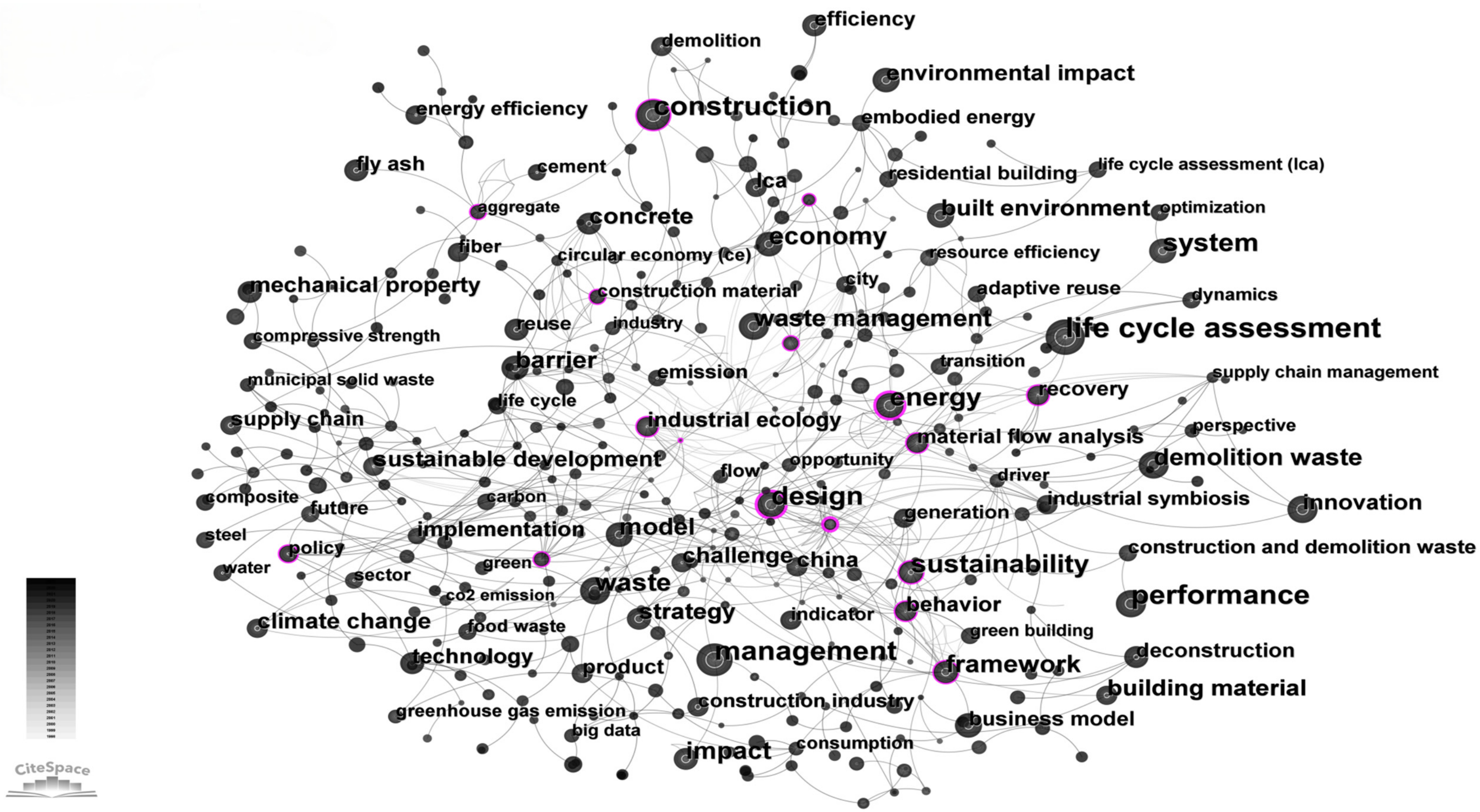

Figure A1. Keyword co-occurrence in the literature search on the circular economy in the construction field (Purple edges indicate high centrality of keywords).

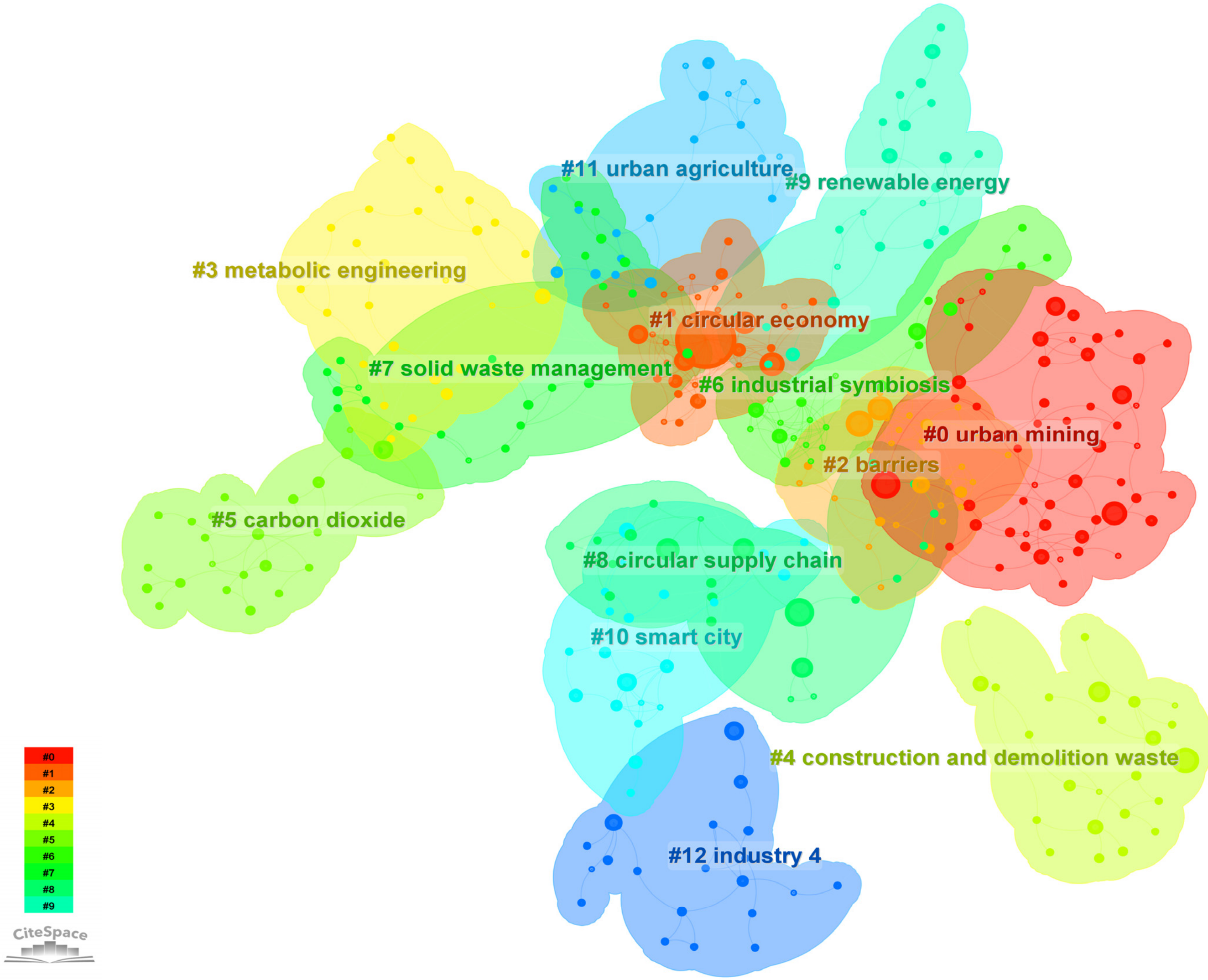

Figure A2. Keyword clustering in the literature search on the circular economy in the building industry.

Figure A3. Keyword co-occurrence in the literature search on straw-bale construction (Purple edges indicate high centrality of keywords).

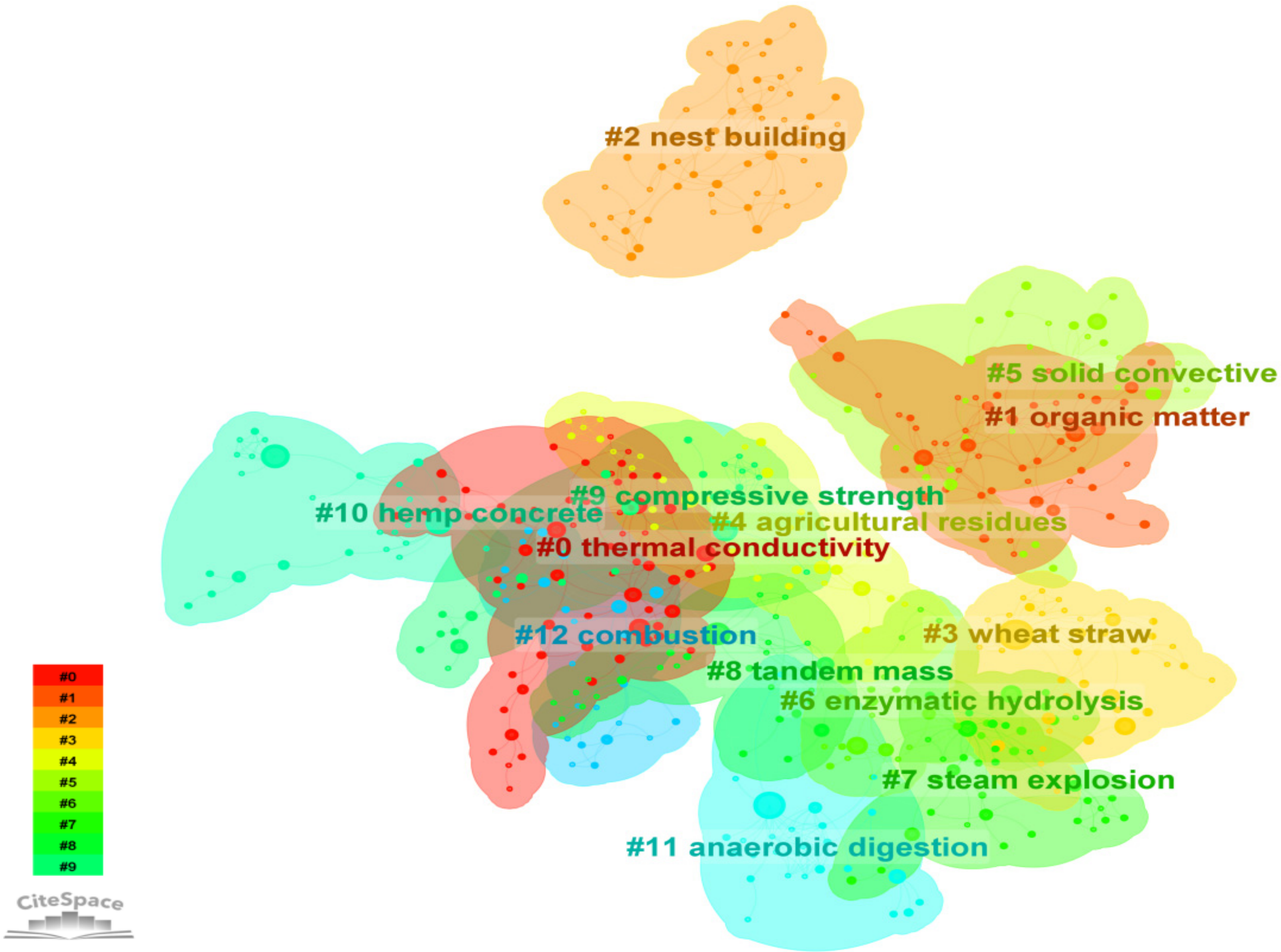

Figure A4. Keyword clustering in the literature search on straw-bale construction.

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