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OPTIMIZING SUSTAINABLE FURNITURE DESIGN THROUGH THE APPLICATION OF AGRICULTURAL WASTE STRAW: AN OPERATIONAL RESEARCH APPROACH

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Research Paper

Abstract: *This research focuses on sustainable furniture design using agricultural waste straw biomass. That is why it brings out the aspect of sustainable development in design, which encompasses the consideration of ecological quality, waste minimization and management of resources. The paper focuses on composite materials that include straw biomass and discusses major steps including material selection, manufacturing technique, and Life Cycle Assessment (LCA). The research uses hot pressing, injection moulding and 3D printing techniques to evaluate bio-composite application of straw for furniture to understand its value in minimising the negative effects on the environment and constituents in a circular economy paradigm. This paper uses the Analytic Hierarchy Process (AHP) to assess sustainable design measures and decision-making models, with difficulties such as consistency of quality and customer affectivity. The results indicate that today's appearance and technological breakthroughs need to be incorporated to enhance the economic feasibility and sustainability of straw. This study serves as a source of applied information and directions on how waste material can be used to address sustainable design of furniture and ultimately, effect change in and improve resou rce use efficiencies within the furniture industry.*

Keywords: *Straw, Furniture, Sustainable Design, Manufacturing Technology, Agricultural Waste Straw*

1. Introduction

Entering the 21st century, with the rapid development of human society, the

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demand for resources far exceeds the earth's supply capacity, resulting in a huge ecological deficit. The development and utilization of renewable energy is an effective way to achieve sustainable social development. At the same time, agricultural activities are essential to maintaining human civilization, but they also produce a large amount of waste, laying the foundation for environmental challenges and untapped opportunities for sustainable practices. Agricultural waste straw resources are a rich renewable biomass resource distributed in countries around the world. Straw refers to the waste by-products such as stems, leaves, stalks, shells, and residues left after the seeds are removed after the plants mature. According to statistics, the annual output of herbaceous crop straw in the world is about 3.9 billion tons, of which grain crop straw accounts for about 74%. Taking China as an example, China is one of the major agricultural countries, producing nearly 1 billion tons of straw every year, of which crop straw accounts for about two-thirds (Akshaya et al., 2023). As a biomass resource, straw is known as the "second green forest". According to statistics, if 100 million tons of straw are added to the production process of composite materials every year, 1.7 billion tons of composite materials will be produced, which is equivalent to replacing nearly 350 million cubic meters of forests and absorbing about 45 million tons of greenhouse gases such as carbon dioxide in the atmosphere (Chauhan et al., 2022).

Agriculture plays an indispensable role in shaping the foundation of society. The impact of the agricultural sector is not limited to food production but also affects ecosystems and natural resources on a global scale. In the face of growing concerns about climate change, resource depletion and environmental pollution, the development of agricultural waste materials is particularly important. The application of straw biomass composites in industrial processes, including material selection, process and manufacturing technology, has become part of the promotion of sustainable development. Furniture, as a daily utensil with huge demand, is an inevitable trend of sustainable development. Designing home products using agricultural waste straw as a material meets the needs of modern sustainable design development. As the world urgently needs to transform into a circular economy, minimize waste and optimize resources, agricultural waste, especially straw, is a path worth exploring. There are countless possibilities for its application in home products.

Decision support frameworks are an essential tool that has been identified as critical to solving sustainable design problems as they provide a structured approach to solving complex decision-making problems, including ways of developing sustainable design by taking into consideration analytical and quantitative methods of evaluating the trade-off of diverse environmental social and economic impacts. With this understanding, the Analytic Hierarchy Process (AHP), a popular operational research technique, is particularly suitable for multi-criteria decision-making concerning sustainability contexts. AHP assists in ordering design options because the decision-making procedure is split into several levels, making it more organized and accurate, as (de Oliveira & Duarte, 2024) indicated.

In addition to AHP, Life Cycle Assessment (LCA) can deliver a systematic approach to assess the environmental effects of materials and processes in a product life cycle. This type of integration has been found to improve sustainable product development by incorporating LCA data with the decision-making accuracy of AHP. This combination is particularly relevant for furniture design because material performance, sustainability and consumer choice must be considered.

The increasing need for sustainability worldwide provokes the need to be creative with renewable and scarce materials. Crop production produces large amounts of agricultural straw, considered sustainable furniture, given its availability, renewability, and eco-innocuous characteristics. Nevertheless, its use could be better developed even in the furniture industry, which might benefit greatly. Agricultural straw has desirable properties, moderate tensile strength, and flexibility and is suitable for composite materials. This use of waste thus conforms to circular economy strategies in the exclusion of more conventional materials such as wood. It helps address the reduction in deforestation and the environmental degradation that comes with the disposal of agricultural waste, as noted by (Zhang et al., 2022).

Research conducted on straw for industrial use highlighted that straw composites can significantly lower carbon emissions and have better resource efficiency than traditional construction materials. As mentioned by Sangmesh et al. (2023), the given material can be used to manufacture durable and appealing furniture parts due to the use of advanced technologies such as 3D printing and hot pressing. Stressing such achievements and discussing the existing challenges concerning sustainable material application would significantly improve this study's relevance and tangible impact on the furniture market.

1.1 Research Question

How does the utilization of agricultural waste straw incorporated in the composite material fall under furniture design as a sustainable practice?

What are the appropriate strategies for manufacturing in utilization of straw biomass in furniture making?

What are the prospects and constraints in the utilization of straw biomass material in light of modern principles of design materials?

2. Literature Review

The existing literature review shows that the research and application of straw materials are becoming more and more extensive. For example, Zhang et al. (2022) outlined the properties of straw fibres and their applications in reinforced polymer composites and explored the mechanical, thermal and morphological properties of straw fibres. Straw biomass is not only used as furniture but will also be highly valued for construction and packaging, making it a vital sustainable material. Recent developments show that it has been employed in the manufacture of environmentally friendly, high-performance composites.

The symbiosis between agricultural waste recycling and sustainable design has been deeply explored. Their life cycle assessment of straw utilization schemes provides valuable insights into the environmental impact of straw materials in various applications. Straw materials are a renewable, degradable and zero-pollution resource that can effectively reduce the emission of harmful gases such as formaldehyde (Versino et al., 2023). Incorporating these materials into everyday products can align consumer behaviour with sustainability principles. Sangmesh et al. (2023) reviewed the development and application of straw-based composite panels in the construction field, discussing the advantages of using straw as a raw material and its potential to promote sustainable practices. The application of straw materials in the field of domestic arts and crafts is mainly straw painting and carving crafts.

In summary, the basic research on straw materials is relatively comprehensive and systematic, and the application fields are mainly energy, feed and industrialization, among which building boards and packaging materials are the most mature. However, the research method of product design based on the combination of agricultural waste straw and sustainable development perspectives is insufficient, and there is a lack of certain material application case studies.

2.1 Basic Research on Agricultural Waste Straw Materials

Wheat straw material is a high-quality original ecological material. Ecological materials do not specifically refer to newly developed new materials, nor are they exclusive new material systems. Ecological materials can be divided into original ecological materials and artificial ecological materials. Original ecological materials include wheat straw, bamboo, reeds, etc., which are materials that can be directly used in nature. Artificial ecological materials are materials that people fully exert their subjective initiative, carry out processing and production, and finally obtain (Arodudu et al., 2020).

At the same time, many artificial ecological materials are obtained by extracting original ecological materials and processing them. It can be seen that the importance of original ecological materials. In the modern product design process, materials involve the entire process of design, production, manufacturing, and recycling (König et al., 2024). Therefore, the selection of materials is crucial, especially in the current situation where the world is facing serious problems of ecological environment deterioration. The development and application of ecological materials have become an indispensable link in the process of realizing a circular economy and should receive extensive attention from all sectors of society.

Wheat straw is the part of the wheat crop after mature threshing. Wheat straw has a short growth cycle and belongs to the grass family. The average length of wheat straw is about 1.3m, and it has 7 parts: stem base, middle stem, stem tip, node, sheath, leaf, and ear (Figure 1). Wheat straw material has unique material properties (A. K. Singh et al., 2024). Physical properties reflect the hardness, tensile strength, water absorption, etc. of the material. The chemical composition of the material can understand the material from a microscopic perspective (Yadav et al., 2024). In terms of physical properties, wheat straw has strong hydrophilicity. Under the same soaking time, wheat straw has stronger hygroscopicity than other crop straws, which is related to the larger gaps in its fibres. In terms of toughness, the toughness will vary depending on the maturity and water content of the straw, and mature wheat straw has poor toughness. When the wheat straw material fully absorbs water, the toughness of the material will be greatly improved, becoming soft and not easy to break.

In terms of mechanical properties, it is positively correlated with the length of the material fibre. Longer fibres can increase the tensile strength of the product. The average length of wheat straw fibres is about 1.5 mm. The fibre lengths of different parts of wheat straw are also different. The length of the fibres in the upper part of the stem is longer than that in the middle and lower parts, with an average length of 2.5 mm (S. K. Singh et al., 2024). Although wheat straw is not as good as wood, rattan and other materials in tensile strength, its plasticity and flexibility are more prominent. From a chemical composition point of view, wheat straw contains cellulose, hemicellulose, lignin and ash (Kalpokaitė-Dičkuvienė et al., 2024) (Table 1).

Table 1: Chemical Composition and Content of Wheat Straw

Material Name	Lignin	Cellulose	Hemicellulose	Ash
Wheat Straw	8%-15%	35%-40%	20%-30%	5%-6%

Wheat straw is a very good polymer material. The preparation of environmentally friendly biomass composites (bio-composites) by combining plant fibre materials with biodegradable plastics has become a research hotspot in the new world and an inevitable trend in the development of materials science.

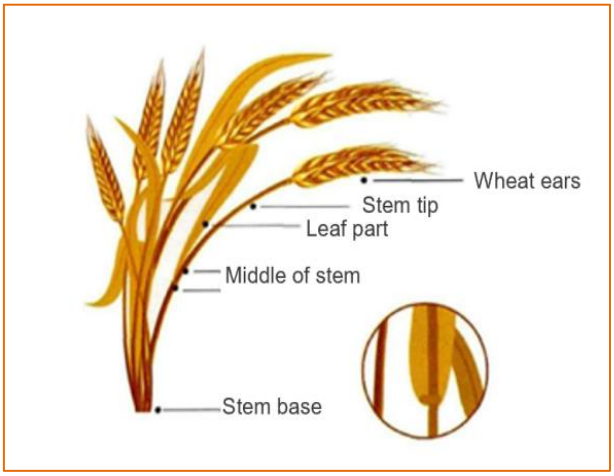

Figure 1: Wheat Straw Structure

2.2 Research on the Application of Straw Biomass Composites in Preparation and Industrial Processes

The basic research on straw materials has been very comprehensive and systematic. Its application areas mainly include energy, feed and industrialization, especially in building boards and packaging materials. The development is most mature (Chen et al., 2022). With the gradual popularization of sustainable design concepts, the rich biomass contained in agricultural waste has received more and more attention. Straw materials are widely used in the manufacture of artificial boards, especially in many fields such as construction, packaging, furniture and outdoor facilities. In the moulding and preparation of straw composite materials, the three main methods are hot pressing moulding, injection moulding and 3D printing technology (S. K. Singh et al., 2024).

Hot pressing moulding is a mixing of natural fibres and plastics into so-called natural fibre-reinforced plastic composites (NFRP), which has become a common standard practice (Friedrich, 2023). This method is increasingly used in the industrial field. One of the representatives is straw plastic composite materials. The hot-pressing moulding of straw plastic composites continues the traditional production process of artificial boards (Xue & Khairi, 2024). The steps of the hot-pressing process can be divided into: mixing straw fibres with thermoplastics and additives, evenly placing them in the mould to form a slab, heating them through a hot press to melt the thermoplastic matrix, and maintaining pressure to cool and shape them. The so-called hot-pressing technology is to pre-press the particles cold first and then melt them in a hot press as depicted in Figure 2.

Figure 2: Hot Press Forming Machine

Injection moulding is an efficient manufacturing process for mass production of parts with complex geometries, consistent quality and aesthetic appearance (Alexandre-Franco et al., 2024). Injection moulding is one of the common methods of polymer processing operations, and 85% of plastic products are achieved through injection moulding. Various factors related to material properties, mould design and process settings will affect the surface quality of injection moulded products. During the injection moulding process, due to high pressure and rapid temperature changes, the polymer melt will undergo various rheological deformations and thermal histories (Vanek et al., 2024). The uneven morphology caused by additives such as reinforcing fibres, mineral additives and foaming agents will also affect the quality and anisotropy of individual parts. Its advantages are a short production cycle, high product quality, and the ability to meet the requirements of complex-shaped products (Fu et al., 2020). This process is not only applicable to all thermoplastics but also to the moulding of some thermosetting plastics with good fluidity as shown in Figure 3 and 4 respectively.

Figure 3 and Figure 4: The Injection of Moulding Machine

Compared with traditional wood, 3D printing technology applied to wood-plastic composite materials can make printed products unique in appearance, without design restrictions, with natural texture, low cost and more environmentally friendly (Nicolau et al., 2022). However, few types of wood-plastic composites can be used for 3D printing. For this reason, researchers have developed a method to compound plant fibres into wood-plastic composites and use them in 3D printing. The compounded fibres can be selected from straw, rice straw, etc., and good 3D printing effects can be achieved under the condition of adding toughening agents. When straw, polyolefins, polylactic acid and other raw materials are added to wood-plastic composites in a certain proportion, the 3D-printed products have good toughness and high impact strength (Pokharel et al., 2022).

Straw composite boards are widely used in board wood furniture. The production process is similar to that of ordinary board wood furniture. The furniture production process (Figure 5) generally covers cutting, polishing, veneer, edge banding, moulding, drilling and painting (Ratnasingam, 2022). The utilization of straw has expanded from traditional feed, fuel and fertilizer to efficient, green and environmentally friendly fields such as bioenergy and building materials. At present, straw has been put into practical use in many industries such as construction, packaging, and furniture.

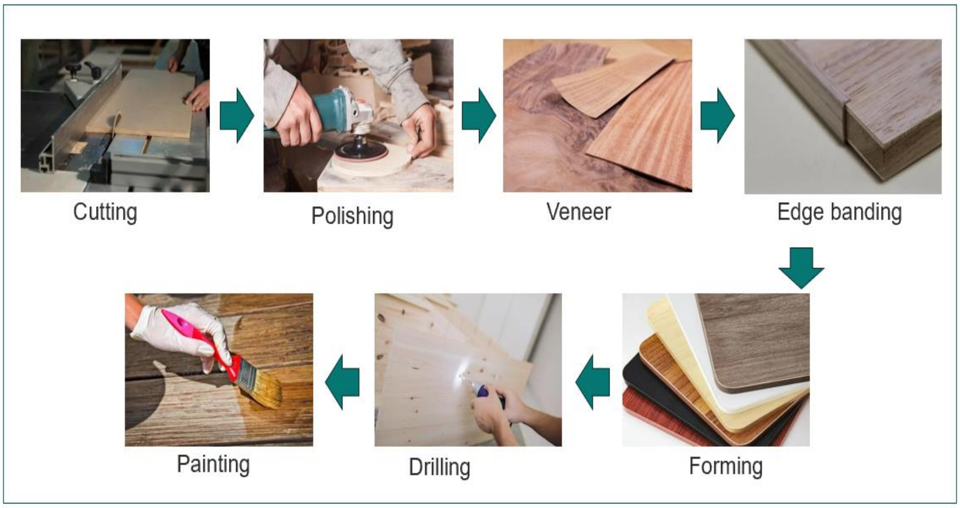

Figure 5: The Furniture Production Process (Baidu.com)

Although straw has shown good application potential in many fields, the market response to products such as straw furniture and straw facilities is still low. Analysis of the reasons found that this is not because of the insufficient performance of straw products, but largely due to the poor integration of materials and product design. The image is not prominent, the connotation is vague, and the design method is too traditional, which makes it difficult to meet the aesthetic needs of modern consumers. At present, straw is mostly used as a substitute for traditional solid wood or artificial boards, and its surface treatment is often done by veneer or paint to cover up the real colour and texture. This overly traditional application method is inconsistent with the potential of straw as a new design material, which can easily mislead the audience's understanding of straw materials and is not conducive to the dissemination of low-carbon and environmentally friendly design concepts (Mutani et al., 2020).

To enhance the commercial value and social value of straw art, future designs need to incorporate modern aesthetics and innovative design methods. At the same time, research on straw composite materials is also constantly improving, including the application of new technologies such as hot pressing, injection moulding and 3D printing. These emerging technologies provide new perspectives for improving the performance and processability of straw composite materials and further broaden their application prospects in sustainable development. Through the advancement of these studies and applications, straw materials are expected to occupy a more important position in future design.

2.3 Research on the Application of DFS Theory in Furniture Design

The concept of sustainable design originates from the concept of sustainable development. In 1980, the International Union for Conservation of Nature (IUCN) and others released the World Conservation Program (WCP), proposing the slogan and concept of "sustainable development". Subsequently, the United Nations established the World Commission on Environment and Development in 1983. In its 1987 research report "Our Common Future", the organization first defined "sustainable development" as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Wojtkowiak & Cyplik, 2020). This shows that human society can achieve economic development and affluent life while maintaining ecosystems and making rational use of natural resources. Sustainable furniture design has become a prominent research field focusing on the relationship between people, furniture and the environment.

As a long-term strategy for mankind to cope with environmental crises, sustainable design has received widespread attention from society and has become an ethical code that designers should abide by. Although the field is still in its infancy, it has attracted the attention of interdisciplinary scholars, seeking to explore new opportunities and innovative perspectives for industrial development (Kirchherr et al., 2023). A bibliometric analysis of furniture design technical literature in the Scopus database was conducted to investigate the network of connections between countries, research centres and scientists involved in furniture design, which is of great significance to the research methods and content of sustainable furniture design (Sydor et al., 2022).

At present, people are considering furniture design under the concept of sustainability more from the technical level of materials, processes, etc. (Cicconi, 2020). Sustainable design is a design activity based on sustainable development, striving to achieve harmonious coexistence and sustainable development between man and nature, society and ecology (Madge, 2023). Furniture is ubiquitous and indispensable in human social life. Its manufacture, use and disposal are closely related to the ecological environment and are inseparable from sustainable development (Yasir et al., 2020). Currently, there are few methodological studies on sustainable furniture design, which are usually systematically reviewed by experts from a research perspective. For example, Bumgardner and Nicholls (2020) considered how green practices in design and communication with consumers can affect or even enhance the competitiveness of design companies.

According to recent studies, straw biomass is becoming more and more realistic as a valuable and reasonable material for product development. For example, Zhang et al. (2022) studied the distribution of lignin in straw biomass and proved more compatibility with polymer composites than projected before. This also discusses newer findings in the chemical nature of straw and how they may be used to enhance properties such as mechanical strengths in composites. On the other hand, Chauhan et al. (2022) mentioned that using straw composites is problematic because there are ongoing issues related to moisture sensitivity and durability of the material when exposed to different environmental conditions. The study noted technological advancement, but the large-scale application of straw-based composites was primarily put in perspective. For this reason, there remains much potential for further study of material treatments and compatibility.

Straw-based material is commonly used in advanced technologies of the current generation, such as three-dimensional printing and press making. 3D printing technology was described by Sangmesh et al. (2023) as a revolution in the fabrication of furniture components that can be made to the precise design and shape with little material wastage. The work showed how straw composites could satisfy aesthetic and functional needs and provided informative proposals for forward-thinking furniture manufacturing. However, Friedrich (2023) pointed out that such advancements were design-efficient manufacturing technologies such as mould injection, hence disregarding their energy-demanding nature such as mould injection. This makes the straw-based materials non-sustainable unless the energy used is renewable. Such criticisms underpin the necessity for the qualified evaluation of the ecological effects of production activities.

The circular economy concept has emerged as the core of discourses on sustainable materials. Chen et al. (2022) used LCA and AHP simultaneously to assess the sustainability of straw composites. According to their research, the use of tools enabled the actors to significantly enhance the decision-making process of selecting more sustainable materials for the environment. On the other hand, Ristau et al. (2023) noted that LCA needed to scale more in small-scale structures, especially in the furniture sector. Their study claimed that whilst LCA presents great insights, its nature and associated costs dissuade small enterprises' adoption. This inequality necessitates the availability of sustainable practice tools to ensure that as many individuals or companies as possible benefit from the innovations.

One is the choice of straw materials for furniture, and another critical aspect is people's perception of furniture made from straw. Sangmesh et al. (2023) noted that through specific and new designs and awareness campaigns, notions have changed positively for targeting niche markets. The study also observed that manufacturers of luxury brands who have introduced straw composites in exclusive premium furniture series have received positive responses because of the path for mass acceptance.

2.4 Hypothesis Development

RQ1: How does the utilization of agricultural waste straw incorporated in the composite material fall under furniture design as a sustainable practice?

H1: *Using agricultural waste straws in the composites for furniture will improve the sustainability concept of furniture design by lowering the ecological imprint of traditional raw materials.*

RQ2: What are the appropriate strategies for manufacturing in utilization of straw biomass in furniture making?

H2: *Efficient energy processing techniques like the use of bio-based adhesives and other optimized strategies of production will enhance the viability and commercial attractiveness of straw biomass as an offering premise for durable and beautiful furniture designs.*

RQ3: What are the prospects and constraints in the utilization of straw biomass material in light of modern principles of design materials?

H3: *However, considering straw biomass as a sustainable material for design, technical issues relating to quality variation, moisture issues, and other conceptions of consumer association will act as barriers to the extensive use of straw biomass for the production of furniture in modern production lines.*

3. Methodology

3.1 Research Methods and Design

This study uses an explanatory quantitative research design to examine the possibility of using agricultural waste straws in furniture production. This activity aligns with the operational research domain; the AHP is explored to devise effective methods of approaching multi-attribute decision-making in material selection/driving manufacturing technology decisions. The AHP model structures the decision-making process into a hierarchy that consists of three layers: the target layer containing strategic goals such as sustainable and efficient furniture design; the criterion layer that contains sub-factors like environmental sustainability, resource efficiency, and technological efficiency; and the scheme layer containing material and manufacturing consideration strategies. Thus, in this way, AHP helps objectively analyse and rank the concepts so that the correct decision, optimum in all respects, can be arrived at out of given factors in terms of significance. Additionally, AHP is integrated into the research design, providing concrete steps to evaluate and rank these concepts quantitatively, allowing for non-biased decisions.

The AHP is acknowledged globally as a sound decision-making approach, especially in material selection and sustainable research. One of the strengths of the AHP is that it systematically breaks down systems into various levels of hierarchy to assess qualitative and quantitative variables. In addition, Dinh et al. (2020) used AHP to evaluate sustainable construction research with the help of the LCA approach to compare different construction materials. Abadi and Moore (2022) also found that AHP of the materials demonstrated higher performance on circular economy compatibility when selecting materials for use and therefore sustains importance in the industries advancing sustainability goals.

3.2 Data Collection Method

Primary and secondary research data was collected during the data collection process. They were obtained from well-defined experiments on the hot pressing, injection moulding and 3D printing on the lateral strength, mechanical strength, thermal conductivity, tensile strength, compression strength and modulus speed of strand composite material based on the straw. These were stressed as tensile strength, resistance to moisture and various emissions in the manufacturing processes. Secondary data was collected from published literature and articles on straw biomass use in composites and manufacturing industries. Scientific databases, including SCOPUS, Web of Science, and Cochrane libraries, were the source of pertinent scientific outcomes and prior experimental results, forming a data analysis dataset.

3.3 Sampling Technique

In this study, a purposive sampling technique was used, and the samples selected were wheat, rice, and corn straw, which are readily available and used considerably in agricultural areas. This approach helped ensure that only the most feasible type of agricultural waste for furniture design was selected from the samples. The study was conducted in rural areas of China and other countries, where large amounts of straw biomass were produced to enhance the ecological and economic applicability of the results obtained. This was done to minimize the variability of the samples to be tested; characteristics such as fibre length, tensile strength and cellulose content were used to screen samples before testing.

3.4 Samples

Analysis was conducted on several straw biomass samples of different types. However, in this case, emphasis was given to wheat straw, mainly biomass, which had already been recommended for use in composite material due to its advantageous characteristics. The research involved testing at least three different straw types, each subjected to three primary manufacturing techniques: hot pressing, injection moulding and three-dimensional printing. Both samples were prepared in the laboratory, and several runs of each manufacturing method (e.g., 10) were undertaken to obtain credible results. Successful breakdown of agricultural waste and variations in performance were established based on the generalization of the findings across other types of agricultural waste but with this sample diversity. The purposive sampling technique applied in selecting wheat, rice, and corn straws is suitable since they are abundant, possess good structural characteristics, and can be used in composite material. For example, wheat straw offers challenging cellulose content and moderate tensile strength; thus, it can be used in bio-composite production. Moreover, it is accessed immensely in agricultural areas; hence, it is cheap compared to other resources.

3.5 Data Analysis Technique

Straw-based composites used statistical data in data analysis to test the effectiveness of the developed materials. In this study, there were three straws and three manufacturing techniques. Analysis of Variance (ANOVA) was employed to determine the extent of the differences in mechanical properties. Regression analysis contributed to understanding the interdependence between composite characteristics (such as strength or stability) and manufacturing parameters (temperature, pressure). Hence, the AHP model was used to prioritize sustainability criteria encompassing environmental factors, cost of production, and consumer preferences. LCA was also carried out to evaluate each process's environmental impact, identifying the amount of CO_2 released, energy used and Environmental Impact Points (EIP).

3.6 Ethical Consideration

The study complied with collecting and handling data with ecological and nonecological responsibilities. In doing this, all the experiments conducted were carried out to minimize the use of resources and impacts on the environment of sustainable research. To retain high objectivity in the study, the research kept reporting methods, results and limitations as straightforward as possible to present exact results. Also, the work involved people who live in regions that use a large amount of straw biomass so as not only to take into account their experience but also to observe the socioeconomic effects of straw usage. Community approval and participation were sought before administering this study, the results of which were in the best interest of the locals and informed environmental activism.

4. Results

4.1 Sustainable Furniture Redesign Strategy

The United Nations defined sustainability as meeting the needs of the present without compromising the ability of future generations to meet their own needs. Embracing sustainable design principles, incorporating eco-friendly materials, and fostering a circular economy mindset are all crucial steps towards achieving a more sustainable and resource-efficient society (Rahla et al., 2021). Sustainable design is a design activity based on sustainable development, striving to achieve harmonious coexistence and sustainable development between man and nature, society and ecology. When conducting sustainable design, to achieve sustainable development goals, it is necessary to comprehensively balance the environmental impact, social impact and economic impact of the design to achieve environmental, social and economic sustainability (Hapuwatte & Jawahir, 2021).

Furniture is a ubiquitous and indispensable item in human social life. The sustainable design of home products should follow the 5R design principles of raw materials and processing technology. Reduce, reuse, recycle, regenerate and re-evaluate are the only ways for future design. These are sustainable design and production principles, including the use of innovative design, recycling, green and environmentally friendly materials, lean production, sustainable design, responsible consumption, and degradable materials (Figure 6).

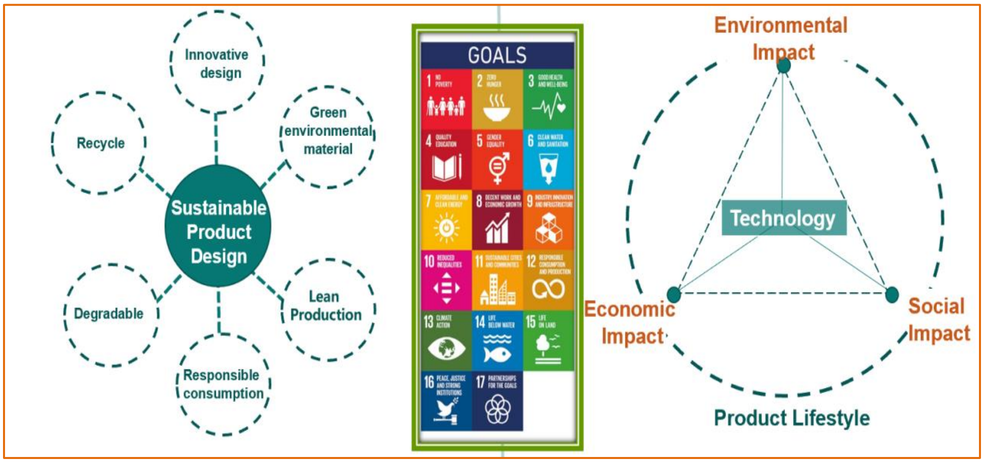

Figure 6: Sustainable Design and Production Principles

These principles aim to reduce the impact of products and production processes on the environment, promote sustainable development, and meet consumer demand for environmentally friendly and socially responsible products (He et al., 2020).

The LCA standardized method studies and analyses furniture from different perspectives to evaluate its sustainability. It is a globally recognized ecological sustainable design strategy that aims to reduce the impact of furniture on the environment during its life cycle. In the design of sustainable furniture, adhere to the sustainability of the life cycle, pay attention to its reuse methods maximize the design of recycling rate, and systematically elaborate the design by straightening out the relationship between people, products, society and nature. Furniture design consists of four elements: materials, structure, appearance and function. Materials and structure are the basis of the entire furniture product. Through the sustainable design concept of furniture, modern technology and traditional craftsmanship are applied to furniture design. Recreate, redesign and re-express waste materials, challenge modern design innovation through the reuse of waste materials, and produce products with little negative impact on the global environment.

According to the life cycle assessment, the current status of sustainable furniture design in the market is divided into four stages: initial design stage, design and manufacturing stage, use and maintenance stage, and end of product cycle (Figure 7). From a macro perspective, micro suggestions in the sustainable design and manufacturing process of furniture are proposed, and different aspects of sustainable furniture design at different stages are explained to find suitable solutions (Aarikka-Stenroos et al., 2022). The furniture design research mainly focuses on the reuse of waste materials and explores the reuse, design and utilization of waste materials according to different stages of the furniture life cycle. There are mainly two types, one is the original design of the raw materials that can be seen from the appearance, and the other is the innovative secondary redesign of materials extracted from waste.

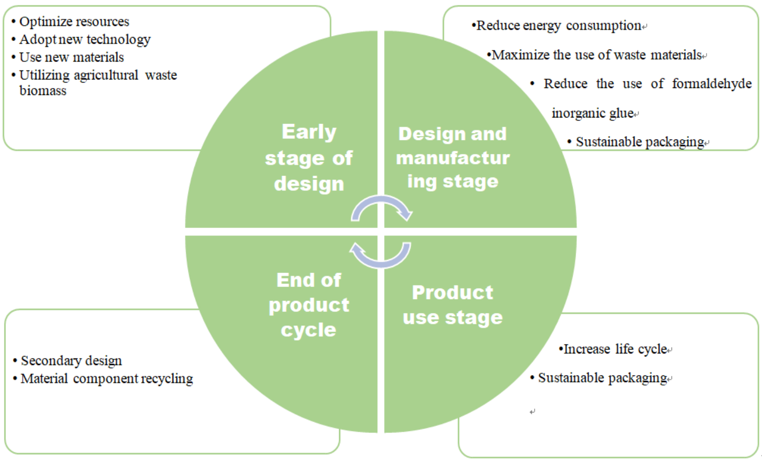

Figure 7: Sustainable Furniture Design Based on Life Cycle Assessment

4.2 Design Method of Original Waste Straw Materials

According to the material, appearance characteristics, and degree of wear and tear of waste straw materials, the characteristic elements of waste straw materials are extracted for design. Maintain the overall sustainability of the furniture product life cycle from the source of furniture design materials and improve the product life cycle (Bumgardner & Nicholls, 2020). For example, to solve the problem of straw burning in rural areas, wheat straw, one of the intangible cultural heritage, is made into a degradable cat bed (Figure 8).

Figure 8: WHECAT Straw Cat, Design by Zhou, 2022

Handwoven also brings income value to local villages, helps rural revitalization, and provides a habitat for urban stray cats.

Both functionality and applicability. Home product design is influenced by design behaviour and design purpose, with function as the core and taking into account material adaptability. In terms of function, modern furniture design needs to be people-oriented, ergonomic, and reflect the functions and characteristics of furniture, such as convenience, comfort, safety, etc. (Lin et al., 2023). In terms of material application, furniture design depends on material considerations, and the material properties of wheat straw must be fully considered. Characteristics such as slenderness, wear resistance, and thin skin limit the scope of use of wheat straw weaving, and it can only be used for furniture decoration. When necessary, wheat straw materials can be technically processed to better meet the requirements of use. For example, JALLU uses wheat straw materials to decorate and design a variety of home product forms, including straw-inlaid headboards and cabinets (Figure 9 and 10).

Figure 9: Straw Marquetry Head Board, Design by JALLU

Figure 10: Straw Marquetry Furniture, Design by JALLU

Based on clarifying the functional form, through technical means, try to launch wheat straw decorated furniture products in different colours to fully meet the personalized needs of consumers in the material application (Setiawan et al., 2023).

As the world faces severe environmental challenges, the renew material brand is committed to helping reduce deforestation and protect the environment. At the same time, it uses the unique and extraordinary material properties of agricultural waste straw to produce and design products that meet market demand. Its products are known for their elegant texture and design (Figure 11). Sustainable design not only refers to recycling and reuse but also includes achieving environmental protection goals by enhancing the product life cycle, reducing pollutant emissions and the use of chemicals (Cucciniello & Anastas, 2021). In the process of innovative design, we must not put the cart before the horse. From design to production, we must reduce the impact on the ecological environment to truly achieve green, sustainable and healthy development.

Figure 11: Heterosexual Chair, Design by RENEW MATERIAL

ANOVA and regression analysis were therefore crucial to analysing the characteristics of the straw-based composites. For instance, the manufacturing techniques were concluded to have statistically significant variations of tensile strength and thermal conductivity as provided by the ANOVA test with p-values mostly below 0.05. Regression analysis went deeper to reveal the magnitude of impacts of certain factors, such as temperature and pressure, on material properties. Taghipoor and Mirzaei (2023) applied ANOVA in bio-composite settings to identify which factors contributed to performance.

4.3 LCA Analysis

The findings obtained from the LCA study are helpful for environmental cost analysis of various production processes and materials selection. Concealing these by particular measures comprehensible as CO_2 emissions, energy consumption, and waste generation demonstrates the benefits of straw biomass as an environmentally friendly material. Substantial energy was required in another technique, injection moulding with moderate CO_2 emissions.

From the materials standpoint, recycling straw biomass has performed well in negating impacts inherent in traditional material use. Straw composites lower overall carbon footprints by 40% less than WCs through renewability and lower embodied energy. In addition, S. K. Singh et al. (2024) reported that straw-based products facilitate the circular economy objectives through decreased waste generation and increased recyclability. Table 2 summarized the hypothesis details.

Table 2: Hypothesis

Hypothesis No.	Null Hyp0othesis (H_0)	Alternative Hypothesis (H_1)	Accepted /Rejected
H1	Using agricultural waste straw in furniture design does not improve sustainability.	Using agricultural waste straw in furniture design significantly enhances sustainability by lowering the ecological footprint.	Accepted
H2	Manufacturing strategies such as bio-based adhesives and optimized processes do not impact the viability of straw biomass.	Efficient manufacturing strategies, including bio-based adhesives, enhance the commercial and environmental viability of straw biomass.	Accepted
H3	Constraints like quality variation, moisture issues, and consumer perception do not impact the use of straw biomass.	Constraints such as quality variation, moisture issues, and consumer perception significantly affect the use of straw biomass in furniture.	Accepted

The finding of this study has significant practical implications for furniture manufacturers interested in transitioning to sustainability. On the same note, straw biomass is relatively cheap, making it a great choice. A. K. Singh et al. (2024) showed that it was possible to utilize hot pressing and 3D printing manufacturing technologies for large-scale production and thus did not require significant investment in new technologies. Similarly, specific market trends show customers will likely embrace conservationism by purchasing goods.

5. Discussion

With the popularization and development of the concept of sustainable development and environmental awareness, the principles based on sustainable design are also developing in real time. The AHP is used to analyse the green ecological design principles as the overall decision of sustainable furniture design, and the design principles are divided into the target layer, the criterion layer and the scheme layer (Xie et al., 2024). The overall target layer positioning does not deviate from the goal of "sustainable design furniture that reuses agricultural waste materials"; the criterion layer is based on the principles of respect for nature (Respect), protection (Reserve), research (Research), memory education (Remember), and reflection (Revalue). The five sub-criteria focus on the ecological balance between man and nature, and study the cyclical development of the product cycle with sustainable development as the ultimate goal to alleviate the ecological load of waste materials on the environment. By redesigning furniture products using waste materials, the environmental sustainability awareness of the user group can be improved.

Reflect and rethink from the perspective of sustainable development, find the entry point for reusing waste materials in design, and achieve the purpose of circular design. The solution layer is mainly based on the core 5R principles of traditional green design, namely Reduce, Reuse, Recycle, Regenerate, and Re-evaluate. It combines the four stages of product LCA and processes waste straw materials during the design and manufacturing stages to reduce material costs and energy consumption. By refining usable elements from waste straw materials and then redesigning and remanufacturing them, the waste materials are reduced and redesigned from the source with a sustainable concept to achieve the goal of circular development (Figure 12).

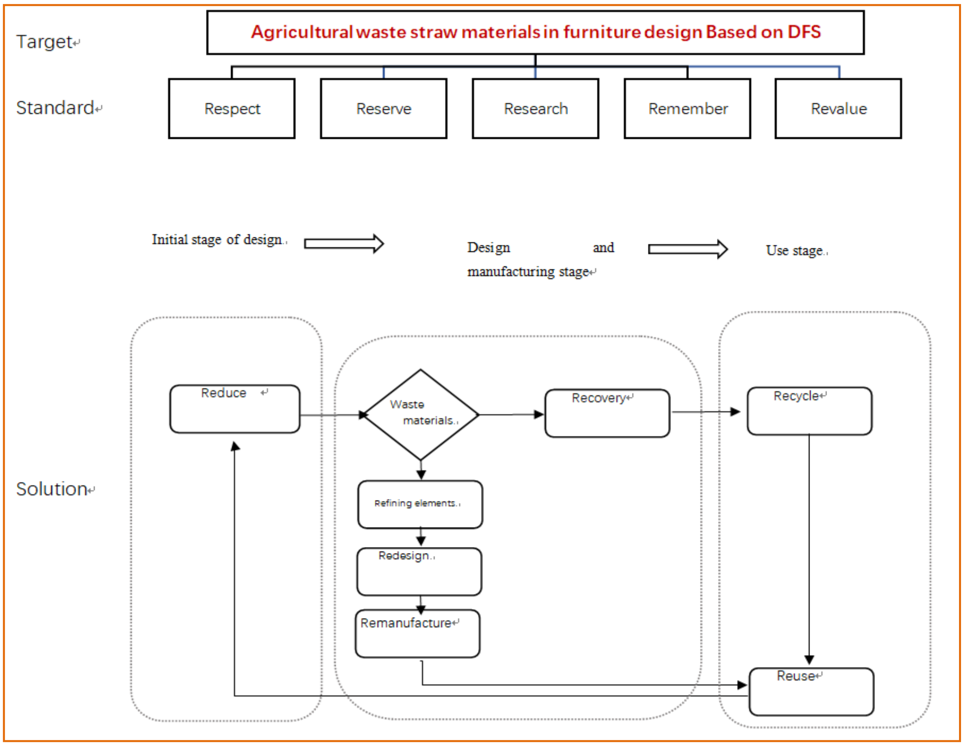

Figure 12: Furniture Sustainable Design by AHP Model

When designing furniture, the function and beauty of the product are designed from the aspects of materials, shape, colour, structure, etc. Materials are the necessary conditions and material basis of furniture. Furniture products not only provide people with basic functions needed in daily life but also bring emotional experience to users when using products (Ristau et al., 2023). Waste materials themselves have certain emotional and nostalgic attributes, and their redesign is a transformation of design thinking (Cross, 2023). People will have characteristic reflections on used materials, furniture and other things. On this basis, perception constructs the user's overall understanding of the product. Therefore, the more things you see, the richer your memory and experience will be, and thus the perception of past things will be richer (Sheng, 2023).

Re-sort and integrate the perceptual characteristics of waste materials in design, grasp the relationship between redesigned furniture and users, and create a unique spatial atmosphere. Waste materials have rich connotations and extensions. Explore the connotation of innovative redesign by reusing waste materials. The design process of furniture that reuses waste materials is decomposed (Figure 13). The design is based on the different characteristics of biomass materials, integrating their visual, auditory, olfactory, taste and tactile perception characteristics so that the furniture products are coordinated with the spatial context and atmosphere (Dominoni, 2024). From a micro perspective, the design of furniture that reuses waste materials is based on the concept of sustainability, and ultimately it is a product that serves people in the spatial context. The intangible value generated by the design of waste materials is much higher than its manufacturing value. The instinctive layer is the basic point of redesign, which comprehensively considers the perceptual characteristics of waste materials and conforms to the basic characteristics of furniture design.

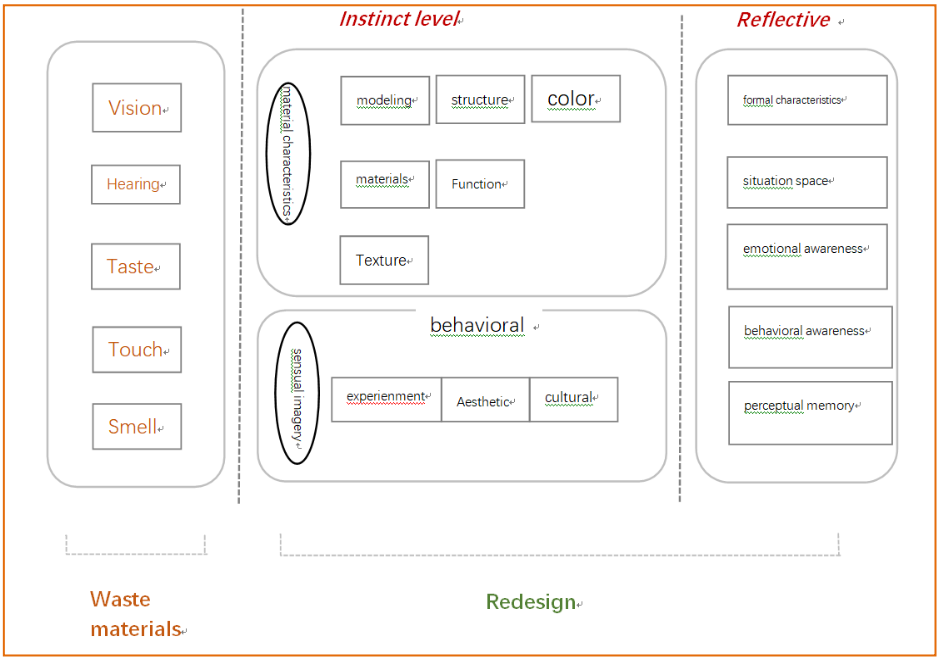

Figure 13: Waste Material Furniture Redesign Process

The behavioural layer of waste material reuse is the core point of furniture redesign. The design behaviour is not only aimed at the extraction of "waste materials". It should not only consider the basic material characteristics of furniture and green design principles but also pay attention to user experience, and explore modern furniture aesthetics and contemporary culture, the reflective level is the value point of furniture redesign. The image of furniture comes from the user's perception of furniture products. Through the formal characteristics of furniture, contextual space, and the emotions and memories of waste materials, it triggers the user's emotions and memories, conveys sustainable design information and its connotation, and realizes the emotional resonance between users and furniture products.

From a macro perspective, social things are interconnected and do not exist in isolation. Furniture is a product that is constantly evolving, designed and manufactured in the human living environment. The design and use process should conform to the harmonious and balanced relationship of the "people-product-environment" while conforming to the circular development strategy of the furniture market to achieve the ecological goals of sustainable development, low-carbon and environmental protection.

Straw biomass has unique, sustainable properties, making it a perfect material for furniture design; comparing it with bamboo, Hemp, and recycled plastics provides valuable context for its use. For instance, bamboo has high tensile strength and regenerative ability among the materials. Growing bamboo involves a large volume of water, thus affecting its environmental consideration. Other materials about which much has been written recently in the 'green building' literature include Hemp, which boasts durability and is even more renewable.

Recycled plastics are highly flexible materials, and they have incredibly long durability. Accordingly, as A. K. Singh et al. (2024) point out, straw biomass is characterized by an affordable price, renewability and a high level of environmental functionality compared with the different alternatives, making it possible to use it for sustainable furniture. Incorporation of the current sustainability standards and reference points would position the study within the paradigmatic processes of the industry. ISO 14040 and 14044 are two life cycle assessment guidelines that must be followed to calculate the effect of the materials and processes to be applied on the environment. Many firms in the furniture industry have used these standards to evaluate resource use and impacts and CO_2 emissions, according to (ISO, 2020). In addition, the sustainability of building materials and products is captured by ISO 21930, which provides more indicators that reflect a circular economy. It is also important to mention other reference points for sustainable practices, such as EU Ecolabel and LEED, which address the question of low-emission and resource-efficient product design.

6. Conclusion

This paper takes the performance of agricultural waste straw and the preparation of bio-based composite materials and their application in furniture design as the research basis, adopting the concept of sustainable design (DS). With the increasing global attention to environmental issues, the furniture industry urgently needs to transform to meet the challenges brought by resource shortages and ecological damage. Therefore, this paper first analyses the characteristics and applications of agricultural waste straw, proves the possibility of straw biomass materials being used in products, explores innovative methods in furniture design, and the development process of sustainable furniture, and divides the life cycle of furniture in the market into four stages: design, production, use and recycling. Under this framework, the source of waste materials is deeply explored from the perspective of design. Further, this paper proposes two sustainable design directions: one is to directly use waste materials for the original design, emphasizing the transformation of the unique properties of materials such as straw into design inspiration to create furniture with aesthetics and functionality; the other is the secondary redesign of element extraction, which gives new life and value to waste materials by reprocessing and combining them. This process can not only reduce dependence on new materials but also effectively reduce the impact of waste on the environment. In the process of exploring furniture design, we start from the perspective of the whole society, emphasize the responsibility of designers in resource use, and encourage them to consider ecological impacts at the design stage. By intervening in the source design of furniture, we strive to reduce the consumption and damage to ecological environmental resources throughout the entire use process and promote the transformation of the furniture industry towards sustainable development.

7. Study Limitations

The first limitation of this study includes the focus on the relatively narrow set of manufacturing technologies (hot pressing, injection moulding, and 3D printing) and straw types (wheat, rice, and corn). Adding to this comparative analysis scope and including other methods and materials besides steel, such as bamboo or recycled plastics, could be valuable. In addition, the study conducted tests at a laboratory scale without considering the conditions of manufacturing industries. Inconsistency of the straw properties is another factor that originates from the regions and different climatic conditions, and it also poses a real challenge when generalizing outcomes. Lastly, the study needs to engage with the industry parties, reducing the relevance of the findings.

8. Study Implications

There are several essential conclusions of this consideration for the furniture business and supporters of sustainability. It will assist manufacturers by presenting an inexpensive and environmentally friendly solution compared to traditional materials, potentially cutting raw materials expenditures by 40%. The possibility of employing hot pressing or 3D printing demonstrated that both approaches can quickly scale up for industrial use. From policymakers' point of view, using straws corresponds to the concept of circular economy; it also helps decrease the amount of agricultural waste and the level of emissions. At last, this research points to consumer motivation for sustainable furniture and proposes an approach to coupling design and environmentally appropriate positioning.

9. Future Research Directions

The outcomes of the present study reveal the potential of straw biomass in sustainable furniture design. However, through various recent literature, future research should apply advanced material treatments to some of the problems, such as moisture sensitivity and durability. Realization of some of the manufacturing technologies that are current in the market, like AI optimization for composite designs, could also enhance production and material performance. Furthermore, extensive exploratory studies based on inaccessible locations and other population types are needed to confirm the market relevance of straw-related composites. Possible developments of the study can be based on conducting longitudinal surveys of consumer acceptance and analysing the effects of governmental policies focused on sustainability on the level of adoption.

References

Aarikka-Stenroos, L., Chiaroni, D., Kaipainen, J., & Urbinati, A. (2022). Companies' circular business models enabled by supply chain collaborations: An empirical-based framework, synthesis, and research agenda. *Industrial Marketing Management*, *105*, 322-339. https://doi.org/10.1016/j.indmarman.2022.06.015

Abadi, M., & Moore, D. R. (2022). Selection of circular proposals in building projects: an MCDM model for lifecycle circularity assessments using AHP. *Buildings*, *12*(8), 1110. https://doi.org/10.3390/buildings12081110

Akshaya, V., Akila, I., Murali, R., Raajasubramanian, D., Kuppan, N., & Srinivasan, S. (2023). Rice Straw Biomass and Agricultural Residues as Strategic Bioenergy: Effects on the Environment and Economy Path with New Directions. In *Bioenergy: Impacts on Environment and Economy* (pp. 139-164). Springer. https://doi.org/10.1007/978-981-99-3002-9_9

Alexandre-Franco, M. F., Kouider, R., Kassir Al-Karany, R., Cuerda-Correa, E. M., & Al-Kassir, A. (2024). Recent Advances in Polymer Science and Fabrication Processes for Enhanced Microfluidic Applications: An Overview. *Micromachines*, *15*(9), 1137. https://doi.org/10.3390/mi15091137

Arodudu, O., Holmatov, B., & Voinov, A. (2020). Ecological impacts and limits of biomass use: a critical review. *Clean Technologies and Environmental Policy*, *22*(8), 1591-1611. https://doi.org/10.1007/s10098-020-01911-1

Bumgardner, M. S., & Nicholls, D. L. (2020). Sustainable practices in furniture design: A literature study on customization, biomimicry, competitiveness, and product communication. *Forests*, *11*(12), 1277. https://doi.org/10.3390/f11121277

Chauhan, V., Kärki, T., & Varis, J. (2022). Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques. *Journal of Thermoplastic Composite Materials*, *35*(8), 1169-1209. https://doi.org/10.1177/0892705719889095

Chen, B., Mohrmann, S., Li, H., Gaff, M., Lorenzo, R., Corbi, I., Corbi, O., Fang, K., & Li, M. (2022). Research and application progress of straw. *Journal of Renewable Materials (JRM)*, *11*(2), 599-623. https://doi.org/10.32604/jrm.2022.022452

Cicconi, P. (2020). Eco-design and Eco-materials: An interactive and collaborative approach. *Sustainable Materials and Technologies*, *23*, e00135. https://doi.org/10.1016/j.susmat.2019.e00135

Cross, N. (2023). *Design thinking: Understanding how designers think and work*.

Bloomsbury Publishing, 1350305073. https://www.bloomsbury.com/uk/design-thinking-9781350305069/

Cucciniello, R., & Anastas, P. T. (2021). Design for degradation or recycling for reuse? *Current Opinion in Green and Sustainable Chemistry*, *31*, 100528. https://doi.org/10.1016/j.cogsc.2021.100528

de Oliveira, B. R., & Duarte, M. A. Q. (2024). Automatic and Semi-automatic Analytic Hierarchy Process (AHP). *Trends in Agricultural and Environmental Sciences*, e240009-e240009. https://doi.org/10.46420/TAES.e240009

Dinh, T. H., Dinh, T. H., & Götze, U. (2020). Integration of sustainability criteria and life cycle sustainability assessment method into construction material selection in developing countries: The case of Vietnam. https://doi.org/10.18280/ijsdp.150801

Dominoni, A. (2024). Design for Sustainability in Space: Future Nature. In *Design for Sustainability and Inclusion in Space: How New European Bauhaus Principles Drive Nature & Parastronauts Projects* (pp. 25-48). Springer. https://doi.org/10.1007/978-3-031-56004-0_2

Friedrich, D. (2023). *Applied Building Physics and Materials Science of Natural Fiber Reinforced Plastics: A Guide for Study and Practice*. Springer, 1350305073. https://doi.org/10.1007/978-3-658-41132-9

Fu, H., Xu, H., Liu, Y., Yang, Z., Kormakov, S., Wu, D., & Sun, J. (2020). Overview of injection molding technology for processing polymers and their composites. *ES Materials & Manufacturing*, *8*(20), 3-23. http://dx.doi.org/10.30919/esmm5f713

Hapuwatte, B. M., & Jawahir, I. (2021). Closed-loop sustainable product design for circular economy. *Journal of Industrial Ecology*, *25*(6), 1430-1446. https://doi.org/10.1111/jiec.13154

He, B., Li, F., Cao, X., & Li, T. (2020). Product sustainable design: a review from the environmental, economic, and social aspects. *Journal of Computing and Information Science in Engineering*, *20*(4), 040801. https://doi.org/10.1115/1.4045408

ISO. (2020). *Environmental management—Life cycle assessment—Principles and framework (ISO 14040)* (International Organization for Standardization, Issue. https://www.iso.org/standard/37456.html

Kalpokaitė-Dičkuvienė, R., Pitak, I., Sholokhova, A., Kriūkienė, R., & Baltušnikas, A. (2024). Surface-Modified Wheat Straw for the Production of Cement-Free Geopolymer Composite: Effects of Wheat Variety and Pre-Treatment Method. *Journal of Composites Science*, *8*(4), 116. https://doi.org/10.3390/jcs8040116

Kirchherr, J., Urbinati, A., & Hartley, K. (2023). Circular economy: A new research field? *Journal of Industrial Ecology*, *27*(5), 1239-1251. https://doi.org/10.1111/jiec.13426

König, K., Mathieu, J., & Vielhaber, M. (2024). Resource conservation by means of lightweight design and design for circularity—A concept for decision making in the early phase of product development. *Resources, Conservation and Recycling*, *201*, 107331. https://doi.org/10.1016/j.resconrec.2023.107331

Lin, Y., Wang, J., & Yang, H. (2023). The Renovation of Fulong Pagoda Park's Landscape Design Using New Light-Storing Self-luminous Materials in Rural Cultural Construction. 2022 4th International Conference on Literature, Art and Human Development (ICLAHD 2022), 25-32. https://doi.org/10.2991/978-2-494069-97-8_5

Madge, P. (2023). Ecological Design: A New Critique [1997]. In *The Design Culture Reader* (pp. 50-60). Routledge. https://doi.org/10.2307/1511730

Mutani, G., Azzolino, C., Macrì, M., & Mancuso, S. (2020). Straw buildings: A good compromise between environmental sustainability and energy-economic savings. *Applied Sciences*, *10*(8), 2858. https://doi.org/10.3390/app10082858

Nicolau, A., Pop, M. A., & Coșereanu, C. (2022). 3D printing application in wood furniture components assembling. *Materials*, *15*(8), 2907. https://doi.org/10.3390/ma15082907

Pokharel, A., Falua, K. J., Babaei-Ghazvini, A., & Acharya, B. (2022). Biobased polymer composites: a review. *Journal of Composites Science*, *6*(9), 255. https://doi.org/10.3390/jcs6090255

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings—from theory to practice. *Applied System Innovation*, *4*(2), 26. https://doi.org/10.3390/asi4020026

Ratnasingam, J. (2022). Automation Technology in Furniture Manufacturing. In *Furniture Manufacturing: A Production Engineering Approach* (pp. 155-167). Springer. https://doi.org/10.1007/978-981-16-9412-7_13

Ristau, S., Desmet, P., & Smulders, F. (2023). Unlocking the experience economy: Integrating design for experience knowledge into fast moving consumer goods (FMCG) product innovation. https://doi.org/10.21606/iasdr.2023.187

Sangmesh, B., Patil, N., Jaiswal, K. K., Gowrishankar, T., Selvakumar, K. K., Jyothi, M., Jyothilakshmi, R., & Kumar, S. (2023). Development of sustainable alternative materials for the construction of green buildings using agricultural residues: A review. *Construction and Building Materials*, *368*, 130457. https://doi.org/10.1016/j.conbuildmat.2023.130457

Setiawan, D., Hidayat, A., Supriyadi, S., & Lestari, W. (2023). Environmental ethics policy in Jepara: Optimization of handicraft designs from wood waste in the furniture industry. *Journal of the Korean Wood Science and Technology*, *51*(5), 392-409. https://doi.org/10.5658/WOOD.2023.51.5.392

Sheng, K. (2023). Exploring the Implementation of Multimedia Technology in Contemporary Home Product Design for Regional Culture Inheritance and Innovation. *International Journal for Applied Information Management*, *3*(1), 24-32. https://doi.org/10.47738/ijaim.v3i1.47

Singh, A. K., Bedi, R., & Khajuria, A. (2024). A review of composite materials based on rice straw and future trends for sustainable composites. *Journal of Cleaner Production*, 142417. https://doi.org/10.1016/j.jclepro.2024.142417

Singh, S. K., Singh, A. M., Gupta, O. P., & Singh, P. K. (2024). Wheat: origin, history, and production practices. In *Wheat Science* (pp. 1-32). CRC Press. http://doi.org/10.1201/9781003307938-1

Sydor, M., Kwapich, A., Lira, J., & Langová, N. (2022). Bibliometric study of the cooperation in the engineering and scientific publications related to furniture design. *Drewno. Prace Naukowe. Doniesienia. Komunikaty*, *65*(209). https://doi.org/10.12841/wood.1644-3985.389.05

Taghipoor, H., & Mirzaei, J. (2023). Statistical predicting and optimization of the tensile properties of natural fiber bio-composites. *Polymer Bulletin*, *80*(12), 13217-13241. https://doi.org/10.1007/s00289-023-04713-9

Vanek, J., Ovsik, M., Stanek, M., Hanzlik, J., & Pata, V. (2024). Study of Injection Molding Process to Improve Geometrical Quality of Thick-Walled Polycarbonate

Optical Lenses by Reducing Sink Marks. *Polymers*, *16*(16), 2318. https://doi.org/10.3390/polym16162318

Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O. V., & García, M. A. (2023). Sustainable and bio-based food packaging: A review on past and current design innovations. *Foods*, *12*(5), 1057. https://doi.org/10.3390/foods12051057

Wojtkowiak, D., & Cyplik, P. (2020). Operational excellence within sustainable development concept-systematic literature review. *Sustainability*, *12*(19), 7933. https://doi.org/10.3390/su12197933

Xie, X., Zhu, J., Ding, S., & Chen, J. (2024). AHP and GCA combined approach to green design evaluation of kindergarten furniture. *Sustainability*, *16*(1), 1. https://doi.org/10.3390/su16010001

Xue, Z., & Khairi, H. (2024). Application Of Natural Fibre Composites In Product Design: A Guiding Framework. *International Journal of Art and Design*, *8*(1/SI-2), 81-95. https://ir.uitm.edu.my/id/eprint/97474/1/97474.pdf

Yadav, S. S., Dhiman, R., & Anklekar, R. M. (2024). *Materials Science and Engineering*. Cambridge Scholars Publishing, 1036402789. https://www.cambridgescholars.com/resources/pdfs/978-1-0364-0277-8-sample.pdf

Yasir, M., Majid, A., & Qudratullah, H. (2020). Promoting environmental performance in manufacturing industry of developing countries through environmental orientation and green business strategies. *Journal of Cleaner Production*, *275*, 123003. https://doi.org/10.1016/j.jclepro.2020.123003

Zhang, L., Larsson, A., Moldin, A., & Edlund, U. (2022). Comparison of lignin distribution, structure, and morphology in wheat straw and wood. *Industrial Crops and Products*, *187*, 115432. https://doi.org/10.1016/j.indcrop.2022.115432