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A Review of Research Progress on Corn Stalk Fiber Biomass Composite Building Materials

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Abstract: ***As a major agricultural country, China has abundant corn stalk resources with high annual output. However, for a long time, a large amount of stalk resources have lacked effective utilization, causing serious resource waste and environmental pollution. Therefore, converting corn stalks into high value-added building materials and structural materials is of great significance for promoting "carbon neutrality" and the recycling of agricultural waste. This paper introduces the research and progress of corn stalks in building materials, focusing on the preparation process, basic mechanical properties, structural applications, and advantages and disadvantages of current corn stalk fiber composite building materials, and points out the existing problems, challenges, and future prospects of corn stalk fiber building materials, providing a reference for further research on corn stalk fiber biomass composite building materials.***

Keywords: Corn stalks, Stalk fibers, Composite building materials, Stalk construction materials, Agricultural waste**.**

1. Main Text

With the rapid development of the social economy, people's demands for green and environmentally friendly practices are increasing, making the use of "green building materials" in construction highly significant. According to calculations, the corn planting area in China has remained stable at over 600 million mu for many years, and in recent years, it has stayed above 650 million mu, with an annual output of around 250 million tons. The annual output of corn stalks accounts for a large proportion of the total stalk yield. Corn stalks are the type of straw with the largest production and the most significant growth in China, with a huge potential for resource utilization that has not yet been fully developed. Meanwhile, research generally believes that traditional straw burning methods have caused serious environmental and social problems, becoming a bottleneck that restricts sustainable agricultural development. In this context, the national promotion of the comprehensive "five-material" utilization strategy, especially the "materialization" utilization approach, provides clear policy support and development space for the application of straw in the building materials sector. Using straw for building material production can not only efficiently dispose of waste but also directly replace some traditional high-carbon footprint building materials, achieving a "win-win" environmental effect, and it serves as a key link between the agricultural circular economy and the green construction industry.

2. Preparation Technology of Corn Stalk Fiber Composite Building Materials

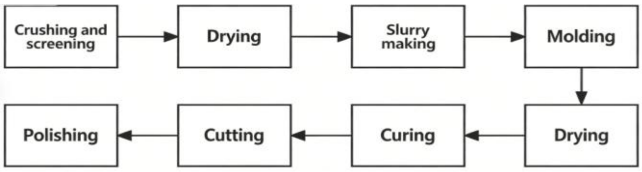
2.1 Preparation Technology of Stalk Fiber

The preparation of corn stalk reconstituted laminated lumber generally includes multiple processes such as raw material pretreatment (removing leaves and pith), fiber separation, drying, gluing, mat forming and assembly, cold pressing and hot pressing curing [9][10]. The technology is developed based on the production techniques of glued laminated timber and reconstituted bamboo, and has been adjusted and optimized according to the characteristics of stalk raw materials. Studies have confirmed that retaining the original fiber structure of corn stalks is crucial to achieving favorable mechanical properties [11]. Compared with the traditional simple crushing and pressing process, the reconstituted lamination process can give better play to the reinforcing effect of stalk fibers and produce high-strength and high-density panels [12].

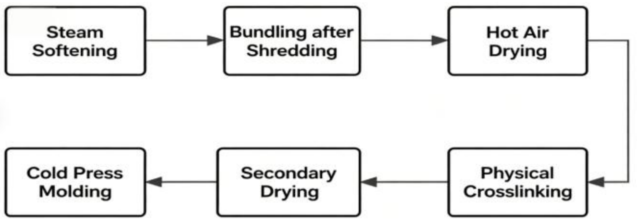
Process comparison reveals that the reconstituted lamination process is fundamentally different from the current mainstream preparation technologies of biomass building materials. In contrast to the traditional crushing and pressing process (in which stalks are completely crushed into powder or random scraps and then flat-pressed), oriented mat forming is the core technical step that distinguishes the reconstituted lamination process from the traditional one. In this process, pretreated corn stalk fibers are carded and oriented along the longitudinal (grain) direction, so that the long axis of the fibers is parallel to the main stress direction of the component, forming an orderly layered or bundled accumulation structure [12][13]. This oriented arrangement fully utilizes the high longitudinal strength and high modulus of stalk fibers: cellulose molecular chains are highly oriented along the fiber axis, with a theoretical strength of more than 1000 MPa, while the transverse direction is mainly bonded by lignin and hemicellulose, with a strength of only 1/10 to 1/20 of the longitudinal direction. By controlling the fiber orientation angle (usually required to deviate less than 15° from the longitudinal direction) with mechanical or air-laid equipment, the maximum load-bearing efficiency of the material in the main stress direction can be ensured. Subsequently, hot pressing is carried out under high temperature (140–180 °C) and high pressure (3–7 MPa) for compaction. Thermosetting resins (such as phenolic resin and isocyanate) flow and fill the gaps between fibers under pressure, and form "spot-welded" rigid connection nodes between fibers after curing, bonding the dispersed fibers into a continuous integrated stress system [10][11]. This process not only increases the material density from the natural bulk density of raw materials (about 0.05–0.1 g/cm^3) to 0.8–1.0 g/cm^3, but more importantly, realizes effective stress transfer between fibers through the anchoring effect of resin, avoiding early failure caused by fiber slippage [10].

In contrast, the traditional crushing and pressing process completely crushes corn stalks into scraps or powder of random length (particle size usually < 5 mm), which are randomly stacked and then hot-pressed. This process results in isotropic fiber distribution. Although the in-plane strength is relatively uniform in all directions, the high longitudinal strength of fibers cannot be fully utilized. Moreover, the randomly distributed short fibers are prone to pull-out or rotation under stress, leading to low stress transfer efficiency [14]. Microstructural observations show that crushed and pressed panels contain numerous fiber ends and voids with uneven resin distribution, and the interfacial bonding is dominated by point contacts, forming a "weak connection" network. In reconstituted laminated lumber, fibers are continuously arranged longitudinally, and resin forms a continuous adhesive layer between fibers, producing "line contact" or "surface contact" strong connections with more direct and efficient stress transfer paths [12]. Such structural differences are directly reflected in the macroscopic mechanical properties: crushed and pressed panels have a longitudinal compressive strength of only 5–15 MPa, a flexural strength of 8–12 MPa, and an elastic modulus of 2–4 GPa, which can only meet the requirements of non-load-bearing panels; while reconstituted laminated lumber has a longitudinal compressive strength of 27.4–33.1 MPa (33.1 MPa for reconstituted substrate, 27.4 MPa for laminated members), a longitudinal tensile strength of 30.2 MPa, a flexural strength of 35–45 MPa, and an elastic modulus of 8–12 GPa. The performance indicators are close to the level of SPF (Spruce–Pine–Fir) dimension lumber and can be used as structural members such as beams and columns [9][18][19].

Compared with glued laminated timber, both adopt the principle of laminated gluing, but glued laminated timber directly uses the original strength of dimension lumber, while corn stalk reconstituted laminated lumber needs to endow the unit with strength through fiber separation and reorganization before secondary lamination to form components, resulting in a longer process chain and higher requirements for interfacial bonding quality [16]. Compared with reconstituted bamboo, bamboo fibers are long and high-strength, and can be directly impregnated and hot-pressed after rolling and defibering; while corn stalk fibers are short with a waxy layer on the surface, pretreatment methods such as steam explosion or chemical modification are required to destroy the surface structure and ensure full wetting of the adhesive [17].



Traditional reconstituted material production process



New Recombinant Material Production Process

Figure 1: Comparison Diagram of Straw Fiber Preparation Processes

2.2 Preparation Technology of Composite Systems

In terms of composite system selection, corn stalk reconstituted laminated lumber is distinct from cement-based stalk composites (which focus on resolving fiber–cement interfacial compatibility, exhibit low strength, and are mainly used for non-load-bearing walls) and polymer-based composites (produced by extrusion molding with fibers dispersed in a PP/PLA matrix, suitable for decorative panels). Reconstituted laminated lumber takes fibers as the continuous load-bearing phase, bonded with thermosetting resin, and forms spot-welded connections between fibers via hot pressing. It can achieve mechanical properties close to those of engineered wood and is suitable for structural members such as beams and columns [20].

Early studies explored the effects of different adhesives (e.g., urea-formaldehyde resin, phenolic resin) and process parameters (density, hot pressing temperature and time) on the performance of stalk reconstituted lumber [14]. With technological advancement, research focus has shifted to process optimization for further improving the uniformity and stability of material properties. In forming technology, the combined cold pressing–hot pressing curing process ensures better thickness uniformity than single hot pressing. In fiber treatment, steam explosion expansion modification significantly increases fiber specific surface area compared with mechanical crushing, leading to an improvement in impact toughness of composite panels by 15.69%–156.74%. In addition, adhesive-free molding technology (utilizing the self-bonding properties of lignin and hemicellulose in stalks under high temperature and high pressure) can eliminate formaldehyde emissions, but shows poorer performance stability than resin bonding, and is currently limited to indoor non-structural applications [9]. For instance, some studies have further laminated reconstituted stalk boards into larger-size laminated members with superior performance to meet the requirements of structural applications [11][19].

3. Mechanical Properties

3.1 Characterization of Basic Mechanical Properties

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Systematic experimental studies on corn stalk reconstituted lumber and its laminated products show that the material exhibits obvious anisotropy in the main mechanical properties such as compression, tension and bending, and behaves as a brittle material as a whole [11][15].

Corn stalk reconstituted lumber shows significant anisotropic behavior under compression. The longitudinal compressive strength is considerably higher than that in the transverse direction, reaching 33.1 MPa (reconstituted lumber) and 27.4 MPa (laminated lumber) respectively [15], meeting the design strength requirements of general wood structural materials. The longitudinal compressive strength of parallel-grain laminated lumber is about twice that in the transverse direction, indicating that the grain direction is a key factor affecting its compressive performance [21]. Failure mode analysis shows that failure under longitudinal compression mostly develops along the bonding interface, while transverse compression manifests in different forms of shear or splitting failure depending on the grain direction, reflecting the direct influence of internal fiber arrangement on the failure mechanism.

Tensile test results show that the longitudinal tensile strengths of reconstituted lumber and laminated lumber are 30.2 MPa and 27.3 MPa, respectively. The stress–strain curve is basically linear before failure, showing typical characteristics of brittle materials with fiber fracture as the main failure mode [22]. Further studies indicate that the ultimate tensile bearing capacity of members is significantly affected by geometric dimensions: increasing length reduces the bearing capacity, while increasing cross-sectional dimensions helps to improve the bearing capacity, both of which show a nonlinear relationship.

As a key performance for beam applications, corn stalk reconstituted laminated lumber exhibits brittle failure under bending load, mostly starting from the pure bending section at the midspan accompanied by the sound of fiber fracture [19][24]. The lamination method has a significant effect on the flexural performance: vertical lamination provides the highest bearing capacity, followed by horizontal lamination, and combined lamination is relatively low [19]. Different lamination methods correspond to different failure modes: horizontal specimens commonly show peeling in the compression zone and fiber fracture in the tension zone; vertical specimens show vertical cracking in the compression zone and finger-joint failure; combined specimens feature both characteristics.

From the perspective of stress–strain response, the material exhibits linear-elastic deformation under both compression and tension until brittle failure occurs. The curves of reconstituted lumber and laminated lumber are highly consistent in the elastic stage, and show certain differences in the later stage due to interface effects and material heterogeneity. Overall, the material has a certain elastic deformation capacity but no obvious plastic development stage, and can be classified as a brittle material [11][15].

2.2 Mechanical Behavior and Design Method of Structural

Members To promote the practical application of this material in building structures, studies have systematically investigated the mechanical behavior and design methods of its basic members (beams, columns, joints). The mechanical behavior of beams under bending load was systematically analyzed by combining experimental tests and finite element simulation. The results show that the section deformation of the beam basically conforms to the plane section assumption, and the load–displacement curve presents a linear ascending stage and a nonlinear softening stage. The flexural capacity decreases with the increase of span and increases significantly with the increase of section height. Based on theoretical analysis and test data, calculation formulas for flexural capacity suitable for this material have been established [19][23]. A comparative study on different grain lamination methods shows that parallel-grain laminated specimens have the highest ultimate flexural capacity and the smallest lateral deformation; vertical-grain laminated specimens are prone to longitudinal splitting failure under eccentric load; parallel-grain units exhibit higher bearing capacity under eccentric compression due to better tensile performance [24]. The shear performance of beams is affected by factors such as shear span ratio, material properties and interfacial bonding strength. Tests show that the ultimate shear capacity decreases with the increase of shear span ratio, and the failure mode is dominated by the development of inclined cracks [25][26]. Combined with the failure mechanism and test results, an empirical formula for shear capacity suitable for this material has been proposed [25]. The stable bearing capacity of axially compressed members decreases with the increase of slenderness ratio, and the failure modes include strength failure and overall instability [15]. The bearing capacity of axially tensioned members is controlled by material strength and has a nonlinear relationship with the geometric dimensions of members. Calculation methods for corresponding axial compression and axial tension capacities have been established, and recommendations for the standard values of material strength have been proposed [22]. Through finite element simulation, the mechanical characteristics of beam–column joints under different connection modes were preliminarily discussed, and the influences of connection forms on joint stiffness, bearing capacity and failure mode were analyzed, providing a basis for the connection design of the overall structure [27].

4. Exploration of the Application of Straw Fiber in the Construction Field

In recent years, green building materials and the circular economy have been widely recognized, and straw construction materials have been well promoted and applied. They have received widespread attention and research. Currently, the main types of straw construction materials in China are as follows: straw bricks, straw-based artificial boards, straw fiber composites with road materials, and so on.

4.1 Straw Bricks

Straw bricks refer to bricks made by using a straw baling machine to organize and compress straw, turning the originally loose straw into dense blocks, which are then cut into bricks. These bricks are stacked to build houses. Their prototype originated in the late 19th century in Nebraska, USA, where local farmers, due to a lack of building materials such as wood and stones, compressed discarded straw into blocks to construct temporary houses. Over time, due to their durability and properties of being warm in winter and cool in summer, they gradually gained popularity. After the 1970s, with the rise of green and environmentally friendly concepts, straw brick technology developed again and spread to regions such as Central America, Europe, and Oceania, becoming an important material in the field of low-carbon construction.

Figure 2: Application of Straw Bricks in Building Structures

Yang Jian [28] prepared corn stalk bricks using corn stalks and special adhesives as raw materials via the traditional cold pressing process. The influence of compression ratio on the initial cold pressing parameters was systematically investigated through compression ratio experiments, support vector machine prediction, and discrete element software simulation. The results showed that compression ratio exerted a significant effect on four initial parameters of stalk bricks (e.g., initial density and compressive strength), with the maximum value increased by more than 30% compared with the minimum value. The prediction by support vector machine was consistent with expectations, and discrete element simulation indicated that a higher compression ratio could densify the internal particle force chains, thereby improving relevant performance, which provided a theoretical reference for process improvement and performance optimization of stalk bricks.

Wang Qilin [29] studied the durability and corrosion resistance of corn stalk bricks through freeze–thaw cycles and mildew tests, offering theoretical guidance for its application and promotion in extreme environments. Freeze–thaw cycle tests (at −20 °C low temperature and 25 °C water temperature) revealed that after 10 cycles, the brick volume increased by 29.08% and moisture content rose by 75.62%; microstructural changes led to macroscopic performance degradation, showing poor low-temperature durability. In the mildew test (30 °C, 85% humidity), no mildew occurred on the bricks due to the strong alkalinity of the adhesive, and the average compressive strength was about 8.87 MPa, meeting the standard for non-load-bearing partition wall materials.

Tests by Zhang Jing [30] demonstrated that stalk bricks retained an intact overall structure with only surface charring after being baked at 3000 °C for nearly 20 minutes. They possessed green properties such as heat insulation, thermal retention, and sound insulation, weighing only one-third of clay bricks (approximately 250 kg/m³), and could be widely used in interior and exterior walls of various buildings. Research by Gu Yi [31] showed that the bearing capacity reached 500 kg/m², which could meet the load-bearing requirements of buildings after prestressing treatment. The material exhibited outstanding toughness, favorable seismic and hurricane resistance, and excellent sound and thermal insulation performance. After protective treatment, it achieved moisture resistance, fire resistance (F90 grade), insect and rodent prevention, complying with energy-saving building standards.

With the national advocacy for the application of energy-saving materials and the recycling of stalks, stalk bricks are lightweight, waste-recycling, eco-friendly, high-quality, simple in process, low in cost, and high in efficiency. They fully align with the development trend of wall materials, possess great market potential, and hold promising value for application and popularization.

4.2 Stalk-Based Wood-Based Panels

Stalk-based wood-based panels are manufactured using stalks as raw materials, mixed with wood in different proportions, and processed through a series of procedures including mat forming, pre-pressing, hot pressing, post-cutting, sanitization, and surface treatment to produce finished panels. According to the processing technology, stalk-based wood-based panels can be divided into two categories: adhesive-bonded panels and adhesive-free panels.

Figure 3: Schematic of Straw-Based Artificial Board

In the furniture sector, stalk-based wood-based panels have received extensive attention. While ensuring the design quality, service performance and sensory effect of furniture, most stalk-based panels are free of formaldehyde at present. Compared with furniture made of wood-based panels, furniture made of stalk-based panels causes almost no harm to human body and exhibits excellent environmental performance. Formaldehyde-free stalk-based panels can be processed by cutting, veneering, assembling and other procedures using the existing processes and equipment in furniture factories, just like wood-based panels. They have great expansion feasibility and broad development space in the fields of children's furniture, office furniture, integral cabinets, hotel furniture and so on [32].

The demand for wood-based panels is particularly large in interior decoration. For example, ceilings need to be fixed with wooden keels and wood-based panels; walls with unique shapes need wood-based panels as a base to ensure a smooth surface and stable substrate for the final decoration effect; some fixed wooden decorative shapes indoors can be made of stalk-based panels instead of traditional wood-based panels; tatami and storage stairs also require wood-based panels [33]. In addition, there are many other applications of wood-based panels in interior finishing. Excessive formaldehyde emission in residences poses a serious threat to human life safety, and people are paying increasing attention to the environmental performance of interior decoration panels. Therefore, stalk-based wood-based panels are undoubtedly the best formaldehyde-free alternative on the market and the preferred material for interior decoration [34].

In the flooring field, wood flooring is deeply favored by consumers for its natural color and texture. However, the rapid growth of wood flooring production will undoubtedly further aggravate the shortage of wood resources. Coupled with the bottleneck of flooring flame-retardant technology at this stage, the efficient utilization of stalk resources and rational application of inorganic adhesives are of great significance. Lu Jie et al. [35] successfully developed corn stalk composite panels, which are superior to commercially available flooring substrates in mechanical properties, sound absorption performance and dynamic thermodynamic properties, basically meeting the requirements for laminated flooring substrates. Zuo Yingfeng et al. [36] applied stalk-based wood-based panels as flooring substrates to prepare composite structural flooring, in which the upper, lower and core layers are veneers and the second and fourth layers are stalk-based panels. This structure effectively improves the surface performance of flooring. In addition, the inorganic adhesive adopted by the research group is environmentally friendly, non-toxic and flame-retardant with smoke suppression effect, which has been promoted and applied in many enterprises and shows broad market prospects.

The emergence of stalk-based wood-based panels provides a new approach for the recycling and treatment of stalks, with promising development prospects.

4.3 Stalk Fiber Reinforced Road Composites

With the rapid development of science and technology and the continuous advancement of transportation construction, stalk fiber has been applied in all aspects of traffic engineering. It can be composited with a variety of road building materials to enhance the tensile strength, deformation resistance and crack resistance of conventional road materials. At present, it can be used for composite modification with common road materials such as asphalt, cement and concrete, greatly improving material performance and service life.

Figure 4: Straw Fibers Combined with Asphalt and Concrete

With the continuous development of highway construction, conventional asphalt pavements can no longer meet service requirements and frequently suffer from loosening and cracking, which seriously shorten their service life. Researchers have incorporated stalk fiber into asphalt mixtures to improve their deformation resistance, crack resistance, and spalling resistance. Xie Dandan et al. [37] optimized the modification process of corn stalk fiber using a three-factor, three-level orthogonal test. Range analysis and variance analysis were employed to reveal the effects of parameters such as NaOH-to-water mass ratio, cooking time, and soaking time on modified corn stalk fiber. The technical feasibility of replacing lignin fiber with corn stalk fiber was verified through rheological performance comparison of asphalt mortars. It was concluded that corn stalk fiber for asphalt modification provides both high-temperature stability and low-temperature crack resistance, and can substitute lignin fiber in asphalt pavement construction.

Cement-based materials suffer from low tensile strength, poor toughness, and uncontrollable crack width after cracking. Scholars have proposed the concept of fiber-reinforced cement-based composites. The emergence of stalk fiber cement-based composites satisfies the construction industry's demands for lightweight, high-strength, energy-saving, and eco-friendly materials. Alkali-modified stalk fibers incorporated into cement-based materials significantly enhance toughness, flexural strength, crack resistance, and thermal insulation performance. Moreover, uniform fiber distribution in cement does not affect the setting and hardening time of cement-based materials. Alkali treatment of stalk fibers benefits the compressive and tensile strength of stalk fiber cement-based composites, with the optimal effect achieved by soaking in 3.5 wt% sodium hydroxide solution for 24 hours [38][39]. A comparative study on the effects of three common crop stalks (wheat, corn, and rice) on cement-based materials showed that wheat stalk fiber outperforms corn and rice stalk fibers in improving the physical and mechanical properties of composites [40].

Natural plant fibers are abundant and have great potential to replace synthetic fibers for concrete reinforcement. Wen Weichao [41] conducted tests on stalk fiber concrete blocks with different dosages to investigate the effects of stalk fiber on the physical and mechanical properties of blocks. The results indicated that stalk fiber concrete blocks with fiber particle size of 0.35–0.50 mm and dosage of 4% exhibited the optimal physical and mechanical performance under the premise of meeting practical engineering requirements. Compared with ordinary blocks, the density decreased by 2.91%, void ratio, moisture content, and water absorption increased by 1.19%, 51.84%, and 11.46% respectively, compressive strength decreased by 18.85%, and flexural strength increased by 2.13%. Adding an appropriate amount of stalk fiber can effectively reduce the self-weight of buildings and further improve seismic performance.

3.4 Application in Low-Rise Prefabricated Buildings

Based on the excellent material properties of new-type corn stalk reconstituted laminated lumber, Ma Ruting explored various application modes of optimized structural-grade corn stalk reconstituted laminated lumber in three prefabricated structural systems, achieving a high degree of integration between architectural structural design and constructional design. It can be applied to three systems: prefabricated homestay buildings, skeleton panel buildings, and panel buildings, with favorable performance and application feedback [43].

Figure 5: Application of Straw in Low-Rise Prefabricated Buildings

The comprehensive utilization industry of stalks still has considerable room for improvement. To break through technical bottlenecks, the key lies in innovation and application. It is necessary to strengthen basic theoretical research and interdisciplinary research on stalk comprehensive utilization, accelerate the introduction and development of high technologies and equipment, and strive for major breakthroughs in the field of stalk application.

5. Problems and Challenges

At present, remarkable progress has been made in the research on corn stalk fiber biomass composite building materials in China. However, a series of problems and challenges still restrict their large-scale industrial application.

1) Uniformity and stability of material properties are critical bottlenecks. As a natural material, the properties of stalks are affected by origin, variety, position and other factors, leading to discrete performance of composite materials [19]. Strict screening and inspection should be carried out.

2) Long-term durability and interface issues need in-depth verification. The water resistance, moisture resistance, corrosion resistance, aging resistance of stalks, as well as the long-term interfacial bonding performance between fibers and matrix, need to be systematically evaluated under more severe environments [7][20].

3) Difficulties in standardization and industrialization are prominent. There is a lack of national or industrial standards specifically for stalk building materials, especially structural stalk laminated lumber, resulting in difficulties in product certification and market access [20]. From laboratory to factory, problems such as process stability, equipment matching and cost control in large-scale production have not been fully resolved [6][7].

4) Contradiction between environmental performance and cost of adhesives. High performance often relies on synthetic resin adhesives, whose environmental friendliness and cost are important factors for promotion [42]. Developing environment-friendly, low-cost and high-performance adhesives or adhesive-free bonding technology is an important direction [20].

6. Conclusion and Prospect

The research and development of corn stalk fiber biomass composite building materials represent an important intersection for responding to the national “dual carbon” strategy, promoting the green transformation of the construction industry, and realizing high-value utilization of agricultural waste. This paper reviews the current research progress of corn stalk fiber biomass composite building materials in China. Building materials produced from corn stalk fiber feature excellent performance and broad market prospects.

Vigorously developing stalk building materials can solve the problem of comprehensive and effective utilization of stalks and effectively alleviate resource waste and environmental pollution. However, more efficient and green production processes and technical support are still required. Stalk building materials have promising development prospects and great potential for wide application.

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