Mechanical and Degradation Properties of Degradable Cover Materials for Sugarcane Leaves

Jing Jiao,[a,b,]* Puwang Li,[c] Xiaohong Huang,[a,c,]* Jihua Du,[a] Zunxiang Li,[d] Xinpeng Liu,[d] Shuhui Song,[b,e] and Yirong Zhou [f]

Mulch was prepared using composted sugarcane leaves, with polyvinyl alcohol and cationic starch as adhesives, through compression molding. The study aimed to investigate the effects of different adhesives on the mechanical properties, thermal oxidative degradation performance, and biodegradability of the covering materials. The results indicated that, when the adhesive dosage was consistent, cover material A, which utilized polyvinyl alcohol as the adhesive, exhibited higher tensile strength and elongation at break compared to cover material B, which employed a blend of polyvinyl alcohol and cationic starch. Specifically, at an adhesive dosage of 20%, cover material A achieved a tensile strength of 0.46 MPa and an elongation at break of 7.72%, representing the highest values among all experimental groups. There was minimal disparity in the thermal oxidative degradation performance between materials prepared with either adhesive; however, a higher quantity of adhesive led to decreased biodegradability performance. After being buried in soil for 120 days, the degradation exceeded 40% for both materials, resulting in loss of their original shape and strength properties. In conclusion, while sugarcane leaves-based biodegradable materials demonstrate favorable degradation performance, further enhancements are necessary to improve their mechanical properties. These materials have potential applications as substitutes for plastic mulch.

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Contact information: a: South Subtropical Crops Research Institute, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang City, Guangdong Province, China, 524013; b: Agricultural Products Processing Research Institute, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang City, Guangdong Province, China, 524013; c: Agricultural Machinery Research Institute, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang City, Guangdong Province, China, 524013; d: Zhanjiang Engineering and Technology Research Center for High Efficient Recycling of Tropical Crop Straw, Zhanjiang City, Guangdong Province, China, 524091; e: Key Laboratory of Tropical Crops Nutrition of Hainan province, Zhanjiang City, Guangdong Province, China, 524091; f: Lingnan Normal University, Zhanjiang City, Guangdong Province, China, 524048;
** Corresponding author: eddweiss@163.com; xiaohong0611@163.com*

INTRODUCTION

Crop straw is a type of agricultural waste material with wide availability, strong regeneration, low cost, and high biodegradability. It also contributes to increasing soil fertility after degradation. As a result, the utilization of crop straw for producing degradable ground cover materials has become a focal point of research.

In recent studies, researchers utilized corn straw and rice straw to create degradable sheets and evaluated their performance on cultivated crops (Yang *et al*. 2020; Gao *et al*. 2022). The findings indicated that the weed-suppressing capability of the two sheet prototype covers was significantly superior to that of traditional plastic film. Furthermore, the plant height and yield were comparable to those achieved with traditional plastic film but notably higher than those from bare land. These results demonstrate the practical advantages of using straw-based degradable cover for crops (Li *et al*. 2023).

Sugarcane leaves are a significant byproduct of sugarcane, with a substantial annual yield. Unfortunately, the majority of these leaves are currently being burned, leading to serious environmental pollution. Only a small portion of sugarcane leaves are utilized for animal feed, resulting in low comprehensive utilization efficiency. While scholars have successfully used sugarcane bagasse to create biodegradable composite materials (Marichelvam *et al*. 2021; Arpitha *et al*. 2023), there is currently no literature on using sugarcane leaves as the primary raw material for producing agricultural biodegradable covering materials. Given that sugarcane leaves contain a large amount of fibrous substances similar in structure and composition to corn straw, they hold great potential for preparing biodegradable ground cover materials. However, it is important to note that direct mulching of sugarcane leaves may lead to the spread of diseases and pests, ultimately affecting the growth of subsequent crops (Zhang *et al*. 2014; Adamchuk *et al*. 2016). To mitigate such potential harm, aerobic fermentation technology can be employed to process sugarcane leaves, thereby enhancing the safety of utilizing sugarcane leaf ground cover. Conversely, in order to achieve bonding of mature materials, it is essential to identify an adhesive with a molecular structure similar to that of the mature materials or one that can react with them. The mature compost material primarily consists of three components: fulvic acid, humic acid, and humin, which contain numerous hydrophilic groups such as phenol hydroxyl, alcohol hydroxyl, and carboxyl groups on the surface and a multitude of benzene ring structures internally. Biodegradable adhesive materials with comparable structures mainly include starch, polyvinyl alcohol, cellulose, among others. Research has demonstrated that the addition of cationic starch can reduce the viscosity of sodium carboxymethyl cellulose (CMC) solution and enhance the mechanical strength as well as water absorption and barrier properties of CMC films (Li *et al*. 2022), while it may lead to decreased tensile strength and elongation at break in polyvinyl alcohol films (Dong *et al*. 2022). Different adhesives have varying effects on the mechanical properties of film materials.

Therefore, in order to innovate the utilization of sugarcane leaves as resources and solve the problem of processing and utilizing a large amount of sugarcane leaves, it is essential to accurately grasp the properties of degradable cover materials for sugarcane leaves. This study utilized sugarcane leaves that were rotted by aerobic fermentation as the base material, with polyvinyl alcohol starch and cationic starch as auxiliary materials. The effects of different adhesives and adhesive addition amounts on the mechanical properties of the mulch were investigated, and the thermal oxidative degradation and biodegradation performance of the prepared mulch samples were examined. The findings are expected to provide a theoretical basis and data support for the research and application of sugarcane leaf degradable ground cover materials, filling a major research gap in this field.

EXPERIMENTAL

Materials

Sugarcane leaves were obtained from the sugarcane research center of the South Subtropical Crop Research Institute, China Academy of Tropical Agricultural Sciences. The reagents utilized in this study were all of analytical grade and procured from Sinopharm Chemical Reagent Co., Ltd.

Preparation of adhesives

(1) Adhesive 1: A mixture of 10 g of polyvinyl alcohol and 120 mL of deionized water was stirred at 500 r/min in a round bottom flask heated in a water bath. The temperature of the water bath was gradually raised to 90 °C, and the stirring continued for 1 h.

(2) Adhesive 2: A solution containing 10 g of cationic starch in 100 mL of deionized water was prepared in a thermostatic water bath at 90 °C. The mixture was stirred for 30 min, and the gelatinized cationic starch was then combined with adhesive 1 at a ratio of 3:7. The resulting mixture was heated in a thermostatic water bath at 90 °C and stirred at a speed of 500 r/min for an additional 30 min.

Preparation of Degradable Mulch Using Sugarcane Leaves

(1) Biomaterial preparation: The dried sugarcane leaves were cut into 5 to 10 cm pieces and then fermented with an initial moisture content of 60%, C/N ratio of 25:1, at a temperature of 65 °C for 20 days. The composted sugarcane leaves were utilized as the material for preparing the degradable mulch.

(2) Mulch preparation: The biomaterial was spread at a thickness of 0.5 cm on a mold measuring 150 mm ×150 mm. The adhesive was sprayed in the amount indicated in Table 1 to completely cover the surface of the fibrous material. After letting the mixture stand for 24 hours, it was compressed by a tablet press at a pressure of 2.0 MPa to produce a mulch sample with a thickness of 2 mm. The test samples are shown in Fig. 1.

Table 1. Addition Amounts of Adhesives in the Preparation of Mulch Samples

Mulch	Adhesive Addition Amount			
	1	2	3	4
A	Adhesive 1 (5%)	Adhesive 1 (10%)	Adhesive 1 (15%)	Adhesive 1 (20%)
B	Adhesive 2 (5%)	Adhesive 2 (10%)	Adhesive 2 (15%)	Adhesive 2 (20%)

Fig. 1. Test samples

Test of Mechanical Properties

The mulch sample for testing was cut into pieces measuring 150 mm × 20 mm. An electronic universal testing machine (SUNS, Shenzhen, China) was utilized to measure the tensile strength and elongation at break. The mean value of three measurements was then calculated.

The swelling degree test was conducted following the method described by Fu *et al.* (2016). The mulch sample for testing was cut into pieces measuring 40 mm × 80 mm. The sample piece with the initial mass M_1 (g) was immersed in distilled water for 20 min and then removed. Any surface moisture was promptly absorbed with filter paper, and the sample was re-weighed to obtain its weight as M_2 (g). The swelling degree S (%) was calculated using Eq. 1 as follows:

$$S = [(M_2 - M_1)/M_1] \times 100\% \quad (1)$$

Thermal Oxidative Degradation Performance

The mulch sample for testing was cut into pieces of uniform size and placed in an electric thermostatic blast drying oven set at 70 °C, separated by partitions to simulate composting. Samples were collected every 7 days.

Analysis of apparent morphology

The material was cut into pieces of 10 mm × 10 mm and sprayed with gold (Hitachi S4800, Tokyo, Japan) on the surface and cross-section. The microstructure of the mulch was observed in a scanning electron microscope (Hitachi S4800, Tokyo, Japan) with a scanning voltage of 15 kV and a magnification of 300 times.

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Analysis of structural analysis

The material was ground into a powder and measured using a Fourier transform infrared spectrometer (Thermo Fisher Nicolet Is5, Waltham, MA, USA). The scanning frequency was 32 times, and the scanning wavenumber range was from 4000 to 650 cm^{-1}.

Biodegradation performance was evaluated following methods described in a previous study (Luz *et al*. 2016). The mulch sample to be tested was heated at 60 ℃ until reaching constant mass and then cut into five rectangular pieces measuring 25 mm ×50 mm each. The piece with the initial mass W_0 (g) was buried in soil at a depth of 10 cm. Degradation residue samples were collected every 30 days, cleaned with deionized water, and then heated at 60 ℃ until reaching constant mass W_t (g). The degradation rate D was calculated according to Eq. 2:

$$D = [(W_0 - W_T)/W_0] \times 100\% \quad (2)$$

Data analysis

The experimental data were organized and plotted using Excel 2010 (Microsoft Corp., Redmond, WA, USA), and infrared absorption spectroscopy was analyzed using Origin 2022 (Origin Lab Corporation, Northampton, MA, USA).

RESULTS

Effects of Adhesives on the Mechanical Properties of Sugarcane Leaf-Based Mulch

Tensile tests were conducted on sugarcane leaf-based mulch samples prepared with two different adhesives. As shown in Fig. 2, the tensile strength of mulch A gradually decreased as the adhesive addition amount was increased within the range of 5% to 15%, while that of mulch B first increased and then decreased in a mild manner. However, as the adhesive addition amount was further increased, the tensile strength of both mulches A and B significantly increased. When the adhesive was added at 20%, the tensile strength of A and B reached 0.46 and 0.28 MPa, respectively, which were 118% and 149% higher than that at an adhesive addition amount of 15%. Furthermore, as illustrated in Fig. 3, the elongation at break presented a similar trend to that of tensile strength; it gradually increased as the adhesive addition amount was increased, particularly for mulch A.

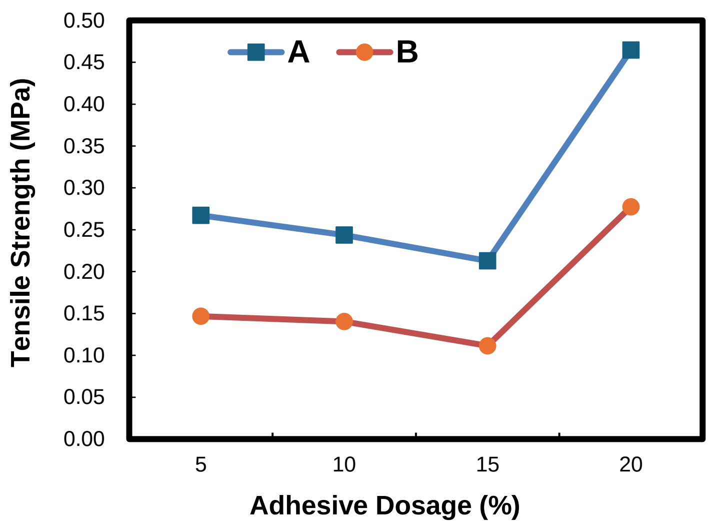

Fig. 2. Tensile strength of sugarcane leaf-based mulch samples prepared with different adhesives at different addition amounts

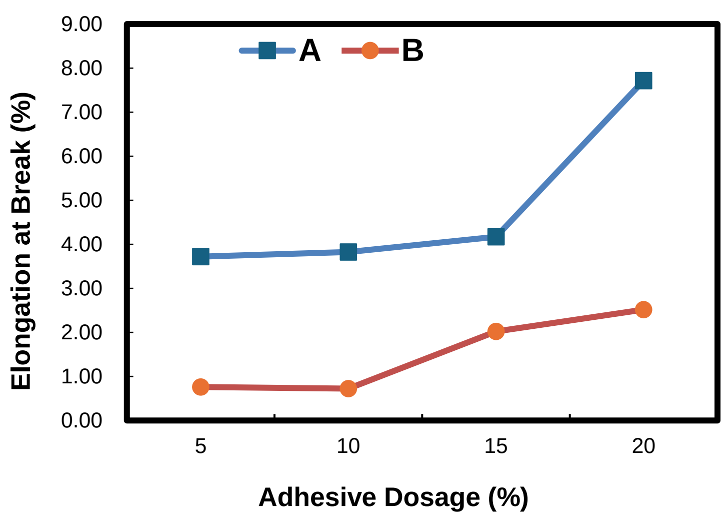

Fig. 3. Elongation at break of sugarcane leaf-based mulch samples prepared with different adhesives at different addition amounts

Figures 2 and 3 demonstrate that both tensile strength and elongation at break for mulch A were higher than those for mulch B when only polyvinyl alcohol was used as an adhesive, indicating significantly better mechanical properties compared to using both cationic starch and polyvinyl alcohol. In summary, adding an adhesive at an amount greater than 15% significantly improved the mechanical properties of sugarcane leaf-based mulch.

Effects of Adhesives on the Swelling Degree of Sugarcane Leaf-Based Degradable Mulch

The swelling degrees of sugarcane leaf-based biodegradable mulch samples prepared with different adhesives varied (Fig. 4). With an increase in adhesive addition amount, the swelling degree initially decreased and then increased, reaching its lowest point at an adhesive addition amount of 10%. At 5% adhesive addition, mulches A and B exhibited swelling degrees above 40%, indicating good water absorption capacity but poor mechanical properties. Mulch B showed the highest swelling degree at a 20% adhesive addition, suggesting strong water affinity due to good compatibility between polyvinyl alcohol and cationic starch. At 10%, 15%, and 20% adhesive additions, mulch A maintained intact morphology. Similarly, at a 20% adhesive addition, mulch B remained intact while the rest appeared as pieces, demonstrating the high strength of polyvinyl alcohol and its good compatibility with cationic starch at higher concentrations as well as the excellent mechanical properties of the mulch materials.

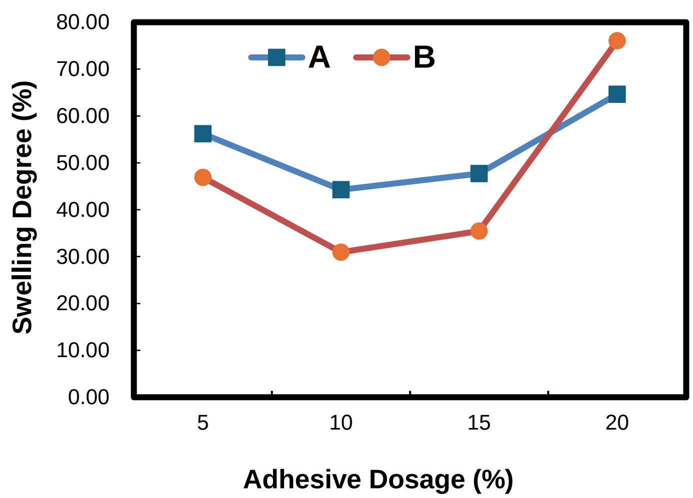

Fig. 4. Swelling degrees of sugarcane leaf-based mulch samples prepared with different adhesives at different addition amounts

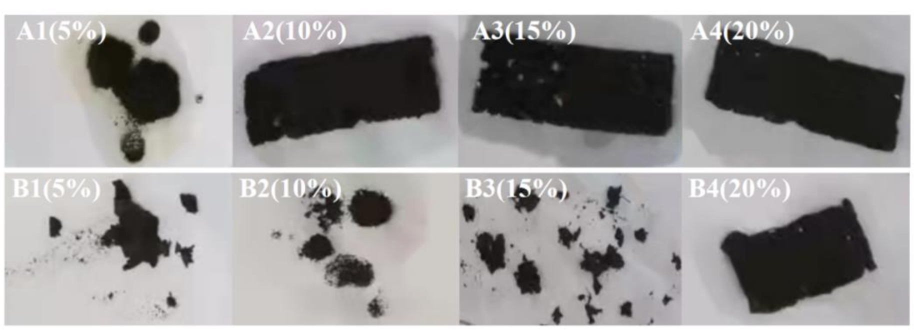

Fig. 5. Apparent morphology of swelling test for sugarcane leaf covering materials

Degradation Performance of Sugarcane Leaf-Based Mulch

Four groups (A2, A3, A4, and B4) of sugarcane leaf-based degradable mulch samples with good integrity were selected for scanning electron microscopy and biodegradation analysis. The changes of the surface and cross-sectional morphology of the samples before and after degradation were observed, and the weight losses of the samples buried in soil were measured.

Scanning electron microscopy

The adhesive formed a layer on the mulch surface, with holes or cracks, which led to the shedding of the adhesive (Fig. 6). This may be attributed to the insufficient amount of adhesive used in all four groups, as it was unable to fully cover the fibrous material. A4 and B4, which had higher amounts of adhesive, exhibited smoother surfaces compared to A2 and A3. After degradation, all four groups showed deformed surfaces (Fig. 7), with the severity of deformation following the trend of A2 > A3 > A4 > B4. This result suggested that the mulch prepared with less adhesive had more unstable surface structure and was easier to be degraded.

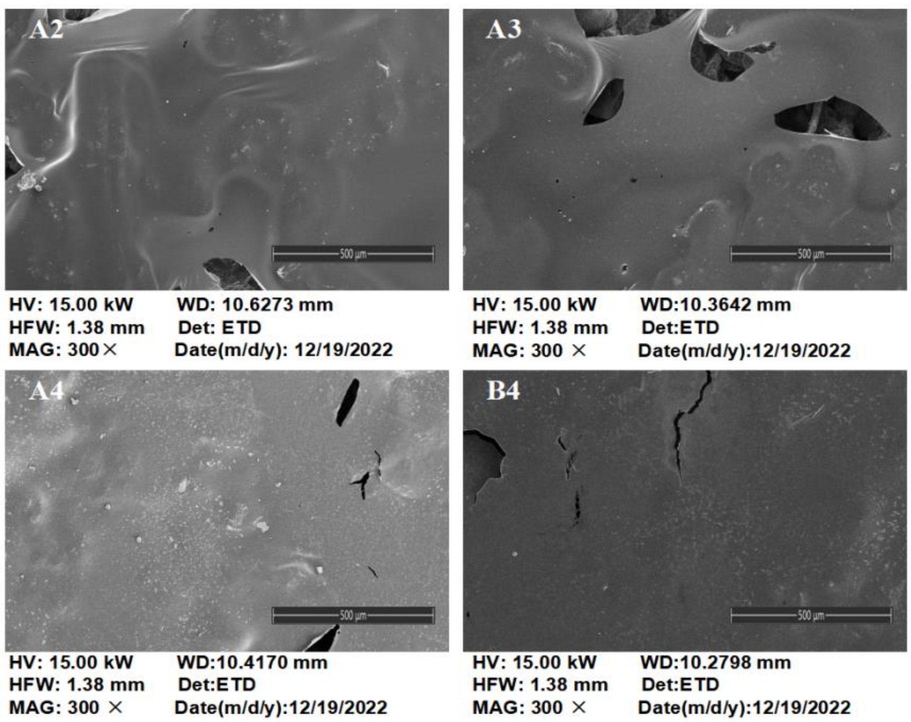

Fig. 6. Microstructure of the mulch surface before degradation

As depicted in Fig. 8, the cross-sections of the mulch samples exhibited similar microstructures prior to degradation, characterized by a dense structure and adhesive that did not penetrate the fibrous material. The lack of encapsulation or adhesion between the adhesive and the leaf matter indicated poor compatibility, resulting in inferior mechanical properties of the mulch. Figure 9 illustrates the cross-sections of degraded mulch samples, revealing a more porous structure in the fibrous material after degradation compared to before. This increased porosity enhanced material contact area, with mulch containing less adhesive demonstrating greater porosity conducive to microbial attachment and subsequent degradation.

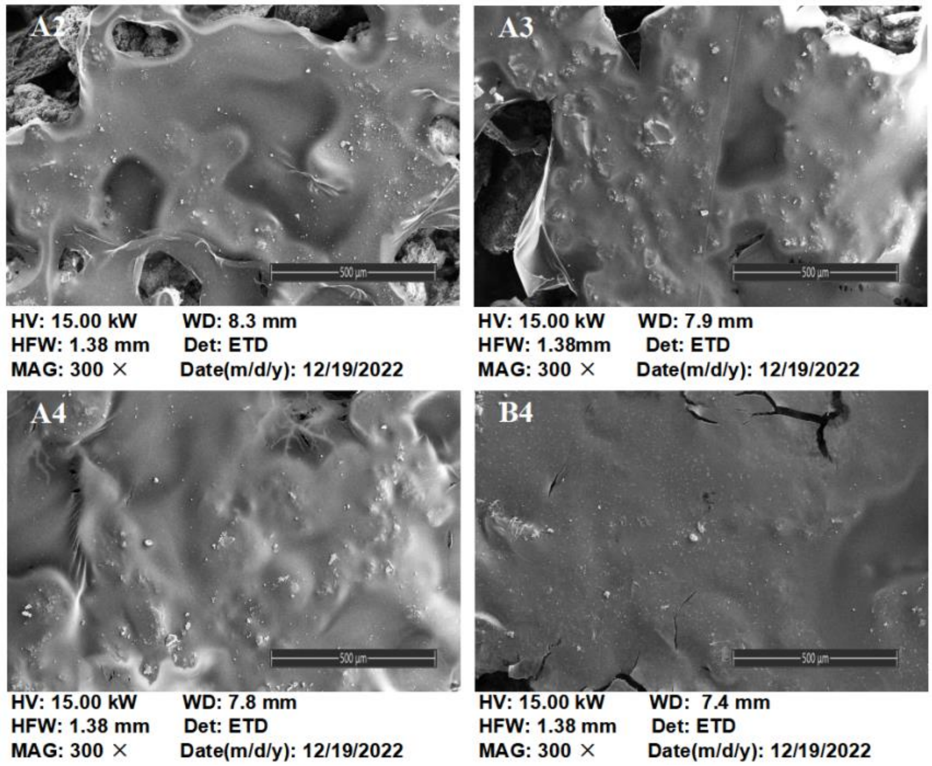

Fig. 7. Microstructure of the mulch surface after degradation

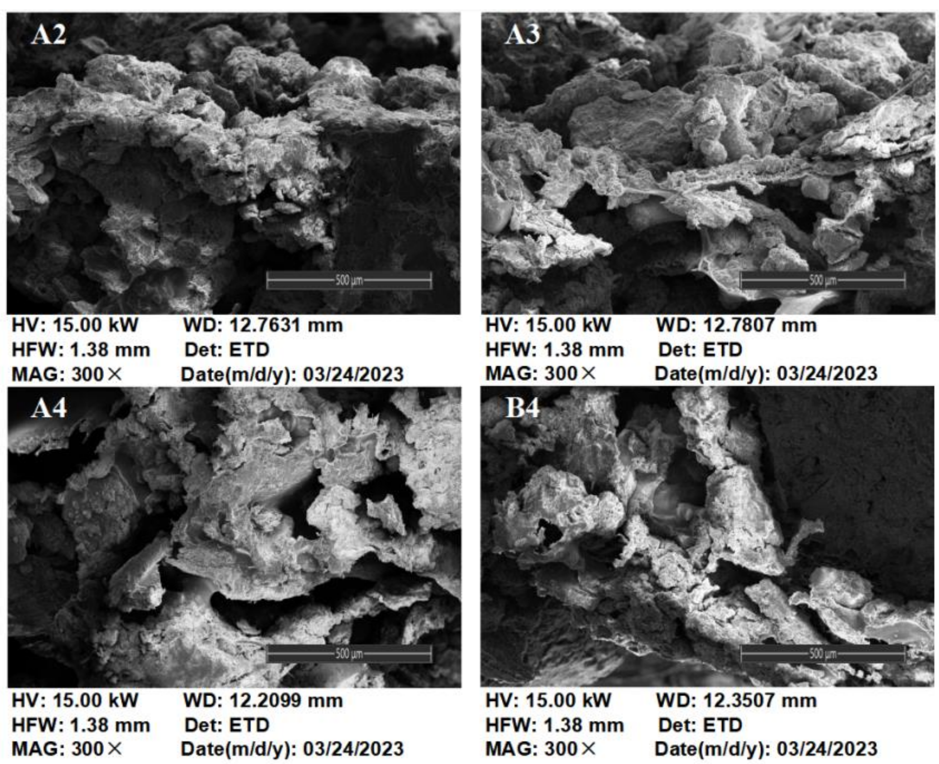

Fig. 8. Cross-sectional microstructure of the mulch before degradation

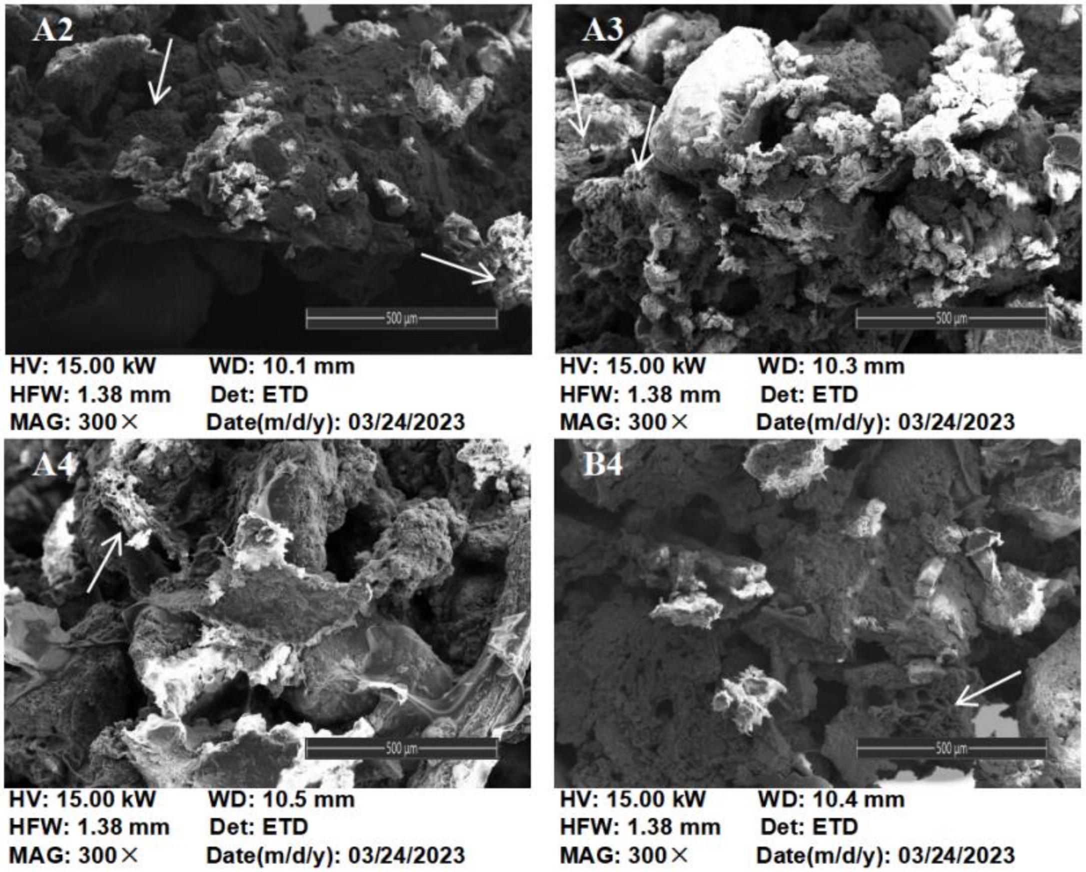

Fig. 9. Cross-sectional microstructure of the mulch after degradation

Infrared spectroscopy analysis

Infrared spectroscopy analysis was conducted on the degradable ground cover material of sugarcane leaves before and after degradation, and the results are shown in Fig. 10. The figure illustrates a strong and wide absorbance band around 3435 cm^{-1} for all four groups of materials, which shifts towards higher wavenumbers and undergoes a red shift after degradation.

This suggests the disruption of hydrogen bonds and other secondary valence bonds between the molecules of the degradable ground cover material of sugarcane leaves, as well as the -OH bonds between the adhesive polyvinyl alcohol/cationic starch molecular chains, resulting in weakened intermolecular force. Additionally, an asymmetric stretching vibration absorption peak for $-CH_2-$ is observed near 2927 cm^{-1}, while an in-plane bending absorption peak for C-H aromatic compounds is observed near 1035 cm^{-1}. After degradation, these main absorbance peaks all shift and the peak pattern becomes flat, indicating macromolecules are cut off during the degradation process and polymerization occurs.

The chemical composition of sugarcane leaf biodegradable ground cover materials prepared with different adhesives is not significantly different, with similar trends observed in changes after degradation across all samples.

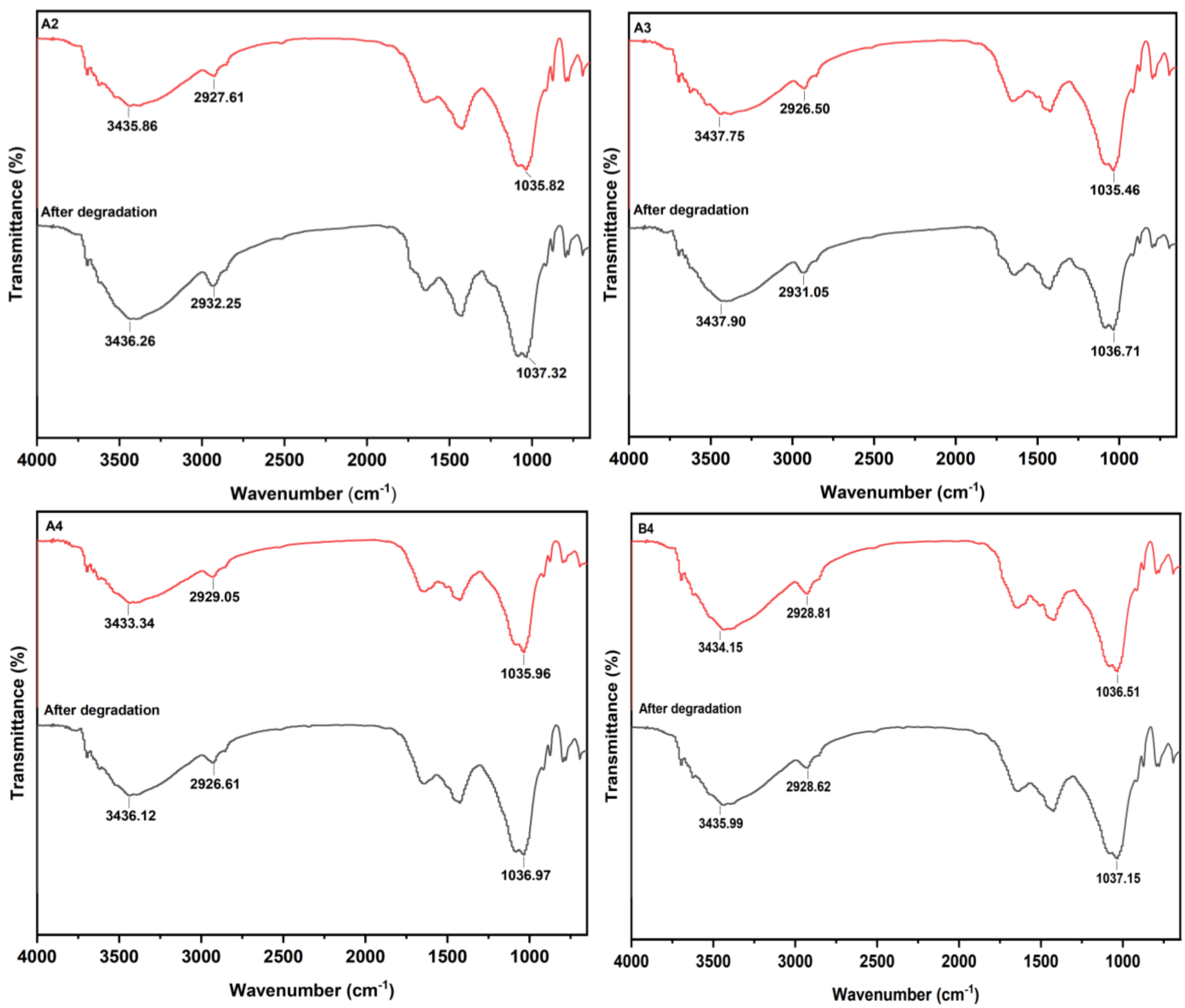

Fig. 10. Infrared absorbance spectra of covering materials before and after degradation

Biodegradation performance

The biodegradation performance of mulch buried in soil for 120 days was evaluated by measuring its weight loss. As depicted in Fig. 11, the degradation extent of the mulch increased gradually over time.

Specifically, on day 90, the degradation extent of mulch sample B4 reached 27.8%, which was significantly higher than that of the other groups. This suggests that the mulch prepared with cationic starch and polyvinyl alcohol as adhesive experienced faster degradation compared to the mulch prepared with only polyvinyl alcohol as adhesive. Furthermore, it was observed that the degradation of mulch A increased slowly before day 90 and then rapidly after day 90.

Additionally, the sample prepared with less adhesive exhibited a higher degradation degree, reaching a maximum of 40%. These findings indicate that mulch A remained stable before 90 days but underwent rapid degradation thereafter. As shown in Fig. 12, on day 120, the mulch samples buried in soil were degraded into small fragments or powder, losing their original shape and strength.

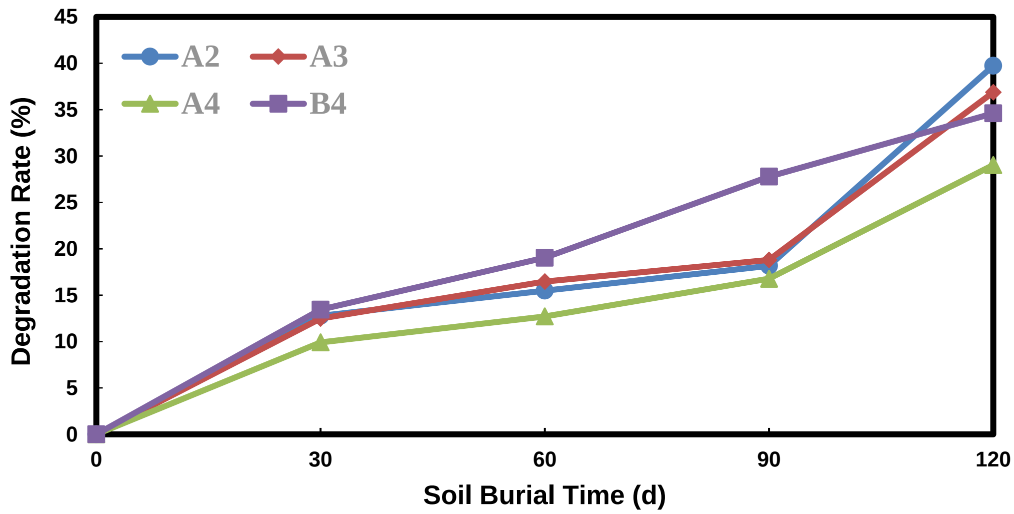

Fig. 11. Biodegradation curves of sugarcane leaf-based mulch samples

Fig. 12. Sugarcane leaf-based mulch samples buried in soil for 120 days (A2, A3, A4 and B4 from left to right)

DISCUSSION

Effects of Adhesives on the Mechanical Properties of Sugarcane Leaf-Based Mulch

After aerobic fermentation, sugarcane leaves are free from harmful substances such as pathogens or weed seeds, making them suitable for mulch preparation. By using polyvinyl alcohol and/or cationic starch as adhesives and composted sugarcane leaves as the fibrous material, a natural mulch with degradability can be prepared through compression at room temperature. The mechanical properties of the mulch were found to be affected by different adhesives and adhesive addition amounts. Specifically, the mulch prepared with adhesive 1 (polyvinyl alcohol) exhibited significantly better mechanical properties compared to that prepared with adhesive 2 (cationic starch:polyvinyl alcohol = 3:7). When the amount of adhesive added exceeded 15%, there was a significant improvement in the tensile strength of cover A and B. Furthermore, at an addition amount of 20% adhesive (14% polyvinyl alcohol + 6% cationic starch), cover B exhibited the highest swelling degree and strongest water absorption ability. This suggests that sheets prepared solely with polyvinyl alcohol as a binder or by combining high concentration polyvinyl alcohol with cationic starch (polyvinyl alcohol > 15%, cationic starch > 6%) demonstrate good mechanical properties, consistent with previous research findings (Huang *et al.* 2023). This is because the circular structure of starch molecules hinders rotation and results in poor fluidity, leading to inadequate adhesion. In contrast, polyvinyl alcohol possesses a simple linear structure and a flexible chain that allows for greater flowability and stronger adhesion compared to starch-based adhesives. The addition of cationic starch weakens adhesion and subsequently diminishes the material's mechanical properties. On the other hand, polyvinyl alcohol has excellent physical properties and degradability, and will not cause pollution to the environment. Compared to cationic starch, polyvinyl alcohol has better physical properties, such as higher crystallinity, durability, and is easier to process and form. Therefore, the use of polyvinyl alcohol as an adhesive is preferred to prepare the sugarcane leaf degradable covering material. However, cationic starch has an excellent price advantage, and it can be considered to add cationic starch to polyvinyl alcohol, but the mixing conditions of these such as temperature and stirring time, need to be further optimized.

When the adhesive was added at an amount greater than 15%, the tensile strength of the mulches A and B significantly improved. Furthermore, when the addition amount of adhesive 2 was 20% (14% polyvinyl alcohol + 6% cationic starch), mulch B exhibited the highest swelling degree and strongest water absorption capacity. This finding suggests that mulch prepared with polyvinyl alcohol alone as the adhesive or with high concentrations of polyvinyl alcohol mixed with cationic starch (polyvinyl alcohol > 15%, cationic starch > 6%) demonstrated good mechanical properties, consistent with previous studies (Huang e*t al.*, 2023). Due to the relatively low cost of cationic starch, the adhesive ratio can be further optimized based on actual demand and cost budget, in line with previous research (Huang *et al*. 2023). However, it is worth noting that the maximum tensile strength of mulch A was only 0.46 MPa, which is much lower than that (5.72 MPa) of thin film material prepared with sugarcane bagasse (Fu *et al.* 2016; Zhang *et al*. 2020). Different preparation processes result in significant differences in the mechanical properties of materials. The thin film material outperforms sheet material in terms of tensile strength, ductility, and softness.

Degradation Performance of Sugarcane Leaf-Based Mulch

The changes in the sugarcane leaf-based mulch before and after degradation were observed using scanning electron microscopy. The surface of the mulch exhibited varying degrees of deformation following degradation, particularly when prepared with less adhesive, resulting in a more unstable surface structure. Additionally, it was noted that the adhesive only adhered to the fibrous material surface without penetrating the fibrous material prior to degradation. This poor compatibility of the adhesive with the fibrous material led to weak interfacial adhesion of the mulch, ultimately contributing to its poor tensile performance. After degradation, the mulch cross-section exhibited a porous structure, which increased the contact area between the material and oxygen, thus facilitating degradation. It was found that the mulch prepared with less adhesive had greater porosity (Li *et al*. 2020). The infrared spectrum analysis revealed that after the degradation of sugarcane leaves as biodegradable ground cover material, there was a phenomenon of depolymerization as the macromolecular chains broke down. This also occurred in the macromolecular chains of polyvinyl alcohol/cationic starch. The rapid degradation can be attributed to the high carbon element and hydroxyl group content in cationic starch and polyvinyl alcohol. During degradation, microorganisms fully utilize these components to promote material breakdown by rapidly reproducing and growing. Additionally, the presence of hydroxyl groups in the mulch allows for easy entry of water into its structure, leading to dissolution and further accelerating its degradation process. To enhance mulch stability, it is recommended to increase the amount of adhesive used in its preparation. The sugarcane leaf-based mulch prepared demonstrated excellent natural degradability. The mulch, which was prepared with polyvinyl alcohol alone as the adhesive, remained relatively stable for 90 days before reaching a degradation rate of over 40% within 120 days. This degradation rate is 50 days earlier than that of the biodegradable plastic film prepared with starch (Guo *et al*. 2024), making it particularly beneficial for short-term crops such as corn and vegetables.

Sugarcane leaves are a significant amount of agricultural waste in hot regions, with abundant resources and great potential for utilization. A biodegradable covering material can be produced by using aerobic fermented sugarcane leaves as the base material, along with cationic starch and polyvinyl alcohol as adhesives, and mechanical pressing to achieve a certain thickness. When polyvinyl alcohol is used as the adhesive, the mechanical properties of the prepared covering material are generally superior to those of the covering material prepared by mixing polyvinyl alcohol and cationic starch adhesive. However, due to the influence of raw material properties and preparation process, the mechanical properties of sugarcane leaf covering material are not as good as those of sugarcane bagasse composite materials. When the dosage of polyvinyl alcohol is 20%, the degradation of the prepared covering material is relatively slow within 90 days of soil burial, showing a rapid degradation trend only after 90 days. This makes it suitable for use in ground cover for short-term crops such as corn and vegetables. The next step should focus on increasing the amount or ratio of adhesive used to further improve the mechanical properties of the covering material. Furthermore, conducting research on the impact of sugarcane leaf utilization on soil and crops will contribute to the advancement of high-performance natural biodegradable materials. This approach also addresses the issues related to pollution caused by sugarcane leaf burning and offers environmental benefits by reducing the reliance on synthetic materials in agriculture. Ultimately, this method presents a new avenue for harnessing the potential of sugarcane leaf resources.

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