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Eco-Innovation: Corn Stover as the Biomaterial in Packaging Designs

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Abstract: Shandong, China's largest agricultural province, generates a massive amount of agricultural waste each year, with corn stover being the predominant type. Although current agricultural waste management primarily involves sustainable practices carried out by professional companies, this study seeks to explore a simpler, more accessible method of handling stover waste. Guided by positivist theory and several experiments, a formula was developed, primarily composed of corn stover powder and natural substances such as glycerin. In this process, we designed and implemented four control experimental groups with water as the quantity used to investigate the influence of different material content in the formula. The resultant material was then subjected to property analyses, including tests on colouration, toughness, etc. Ultimately, the material was applied in a small-scale test as a raw material for an agricultural product packaging design. The study, rooted in sustainability, environmental protection, and the establishment of a local circular economy, fills the gap in current research of lacking design knowledge interventions.

Keywords: bioplastics; packaging design; sustainable design; corn stover; agricultural wastes

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1. Introduction

China is a major agricultural country. According to World Bank data [1], China's agricultural added value reached USD 1.28 trillion in 2021, accounting for 31.1% of the world's agricultural added value. China's agricultural development is rooted in a rich farming civilization history and abundant resource types. Shandong is known as China's number one agricultural province and the only major agricultural province among the top four economic provinces (Guangdong, Jiangsu, Shandong, and Zhejiang).

Shandong has a cultivated area of 12,558.3 million acres for food crops, generating 35 million tons of crop straw each year. The straw, generally referring to the remains of wheat, rice, corn, and other crops after harvest, has been a hot direction for sustainable design research in recent years. Traditionally, straw treatment in China was straightforward—burning. Burnt straw can be used as fertilizer, but it poses significant environmental pollution. Thus, many scholars have proposed targeted solutions to alleviate the issue. For example, Rojas et al. (2019) discussed the potential of materials based on agricultural residue straw and corn husks for a sustainable architectural design, aiming to mitigate the adverse environmental impacts of traditional insulation materials [2]. The sustainable architectural design mentioned here refers to the sustainable design for building exteriors that often involves cultivating plants on exterior walls. Moreover, there are many studies on the application of corn stover in material science, including Wang et al.'s (2019) study on fuel production in lignocellulosic biomass [3], Chen, Wu, and Opoku-Kwanowaa's (2020) research on the application of agricultural waste to soil to improve soil fertility [4], Raheem et al.'s (2022) exploration on hydrothermal carbonization in improving the management and better use of agro-waste [5], etc.

However, most of these studies are from the perspective of material science. Although there are some studies on agricultural waste transformation and its application in design from a designer's perspective, they are few in number [6]. Examples include the use of potato skins to make French fry containers in Figure 1 created by three Italian designers: Simone Caronni, Paolo Stefano Gentile, and Pietro Gaeli. This design practice and various types of sustainable packaging design are essentially using related waste materials.

Figure 1. The French fry containers made by potato skins.

Corn, as a major food crop, has important applications in the field of bio-based chemicals, bio-based plastics, and bio-based fibres. However, as previously stated, existing studies have mainly explored from the perspective of material science, and the experimental processes have been complex, requiring specialised equipment or laboratories to conduct relevant research, significantly increasing the difficulty of straw waste treatment [7].

2. Biomaterials and Corn Stover

2.1. Biomaterials and Recycling

The demand for food production has been driving an increase in the generation of agricultural industrial waste. As early as 2011, according to estimates by the Food and Agriculture Organization, a third of the food produced for human consumption was lost or wasted, equivalent to about 1.6 billion tons annually [8]. Against this background, sustainability has been deeply embedded in the development of most industries, thus encouraging the strengthening of the connection between these concepts, activities, and development in any social project [9]. Within the concept of sustainable development, the notion of waste tends to be eliminated through conservation, recovery, or recycling processes, allowing resources to be used for as long as possible [10]. Therefore, in the context of the growing global pressure of agricultural industrial waste, various parties in society have made many efforts in recent years to improve waste management systems, or to adopt better ways to recover waste as raw materials to produce high-value products, thus reducing food processing and agricultural waste accumulation [11].

In the past few years, the interaction between biomaterials and renewable technologies has created opportunities for the development of new, effective, and sustainable solutions [12]. Due to the necessity of finding alternatives that are more feasible than traditional materials, many scholars in recent years have paid significant attention to the development of renewable resources [13]. The fundamental requirements for renewable energy production depend on the advancement of green technologies, especially in the context of bio-compatible materials that match the performance of existing materials, as they pave the way to a better future [14]. Bio-based means that an industrial polymer that is all or partly composed of natural sources will include plants (such as corn, sugarcane, cassava, or other forms of cellulose), animal and marine materials (such as shrimp shells) and their proteins and chitosan, bacteria, etc. [12,15]. Biodegradability can be understood as when some of the material is extracted from biomass and biodegradable materials, the product is organic, because it can be decomposed into natural water, CO_2, and compost by microbes over a sufficiently long period (within 6 months) [16]. Interest in nature-based materials emerged in the early 1990s as a so-called emerging field.

Biomaterials have existed for 50 years and are still developing at a super-fast pace. The biomaterial market is expected to be around USD 245.6 billion by 2028 at a CAGR of 16% in the given forecast period [17]. Now, as innovative bio-based substitutes, more and more are being used in product design, and biomaterials are becoming a viable alternative to traditional plastics and their uses [18]. The French Atelier Luma Experimental Centre, established by the Arles Art Centre Luma Arles in 2016, aims to develop biomaterials as the cornerstone of a new social model [19]. Figure 2 is a salt brick decoration developed by the centre, all of which was locally sourced. In addition, the floor tiles developed by Mogud using mycelium composite cores also have very high practical value, and their surface is coated with a patented formula, making the bio-based content of the designed products very high. Pascoli et al., (2023) explored using agricultural waste for nanocellulose production, revealing a simple, adaptable process for creating unique nanofibers. They investigated various waste biomasses, showcasing successful nanofiber production and laid groundwork for customizable nanocellulose with diverse applications [20]. Oliveira et al., (2018) conducted tests on biopolymer coatings to validate their effectiveness in preserving the chemical and sensory properties of fruits and vegetables. Coatings were synthesised based on corn starch, cassava starch, and gelatin, with the addition of beeswax as a hydrophobic agent. The experimental process effectively confirmed the waterproofing functionality after the incorporation of beeswax [21]. Arif et al., (2022) explored biopolymeric sustainable materials and their emerging applications. Authors argue that advancements in polymer science and engineering have steered attention toward the use of petal materials to reduce the environmental impact of traditional synthetic plastics. Biopolymers are environmentally friendly, versatile in chemical applications, sustainable, biocompatible, biodegradable, inherently functional, and eco-friendly materials. They exhibit significant potential in diverse applications such as food, electronics, agriculture, textiles, biomedicine, and cosmetics. The authors specifically emphasise that biopolymeric sustainable materials present a favourable solution to address contemporary environmental crises [22].

Figure 2. The salt brick and Mogud mycelium brick.

2.2. Corn Stover in the Context of Mainland China

In China, straw resources are abundant, but their utilization value is low. Agricultural residues are often discarded in the fields to rot or burn in other ways, causing severe air pollution [8]. Since 2014, the Chinese government has issued policies banning the open-air burning of waste and has gradually encouraged many sustainable treatment schemes and policies such as returning straw to the field. However, due to high costs, slow decomposition speed, and low compensation, to date, most farmers as primary producers still have a somewhat repellent attitude toward sustainable treatment methods [10]. At the same time, plastic pollution remains one of the greatest challenges facing the global environment. It is estimated that the pollution generated by global plastic production and incineration in 2019 alone was equivalent to the emissions of 189 coal-fired power plants [12]. The bulk of plastic pollution is composed of single-use plastics commonly used in consumer goods, such as plastic packaging, bags, and containers [13]. Every second, approximately 160,000 plastic bags are consumed globally, of which less than 3% are recycled (Forbes, 2020). Among these, food packaging is thought to account for nearly two-thirds of the total packaging waste [16].

The practice of producing biomaterials is considered to be greatly beneficial in relieving environmental pressure. Nowadays, corn waste, due to its rich cellulose content, has been proven suitable for use as reinforcing fillers for bioplastics and has the potential to be used extensively in the development of composite biomaterials [20]. Incorporating waste from cornfields into the production of biomaterials allows the roots, leaves, and other waste remaining after the harvest of corn crops to enter the processing production line like primary crops, transforming from garbage to raw material. Under the influence of interests for farmers and processing producers, field waste can be viewed as having the same value as edible parts, which can be consciously collected, transported, and centrally regenerated. On the other hand, the degradability of biomaterials themselves can also help alleviate plastic pollution pressure. The production process of most biomaterials tends to use natural organic compounds or non-toxic inorganic additives, effectively reducing pollution emissions in both the production and recycling processes.

In conclusion, this study explores how to further reduce costs and efficiently utilise corn stover, an agricultural waste, to redesign and produce practical biomaterials suitable for product packaging. The particular highlight lies in this study not only delving into the recovery process of agricultural waste and providing the final formula's composition, but also conducting packaging design tests and realizing practical applications for the resulting film. From a comprehensive perspective, this study integrates multidisciplinary knowledge, conducting research spanning the entire process from initial experimentation to the practical production phase.

3. Methods

The experiments of this study began in September 2022. Given the potential application of corn waste in biomaterials, this research experimentally analysed material characteristics under different proportions and designed an agricultural product packaging based on these characteristics. To achieve this, three objectives are presented here: 1—Determine a formula for raw material packaging through quantitative control experiments. 2—Finalise the collection process for necessary materials and the sources of auxiliary materials. 3—Conduct practical tests to assess the various characteristics of the materials.

3.1. Confirmation of the Formula

The method used in this research does not require high technical thresholds and can easily be set up in places where the raw materials are produced. It is even considered advantageous for creating a self-cultivation model in remote areas [10]. Also, biomaterials are considered to increase local productivity and generate new alternatives and more sustainable development methods to support local producers [12], which is in line with the concept of a circular economy. The process of using waste as raw materials is one of the main actions in improving the existing resource utilization promoted by the circular economy [13,23].

During this research process, the breaking and reorganizing of raw materials were the foundational steps for the development of most new material forms. The "Bioplastic cook book [24]" based on the DIY experimental method provided a prototype for the proportion of biomaterials. The main reference formula for this was derived from Dunne (2018), who developed a biomaterial using gelatin and clay powder, and the basic formula consists of ingredients such as biopolymers, plasticisers, solvents, etc. [24]. This formula was chosen as the primary reference for three reasons. First, this formula requires minimal infrastructure facilities, has a low threshold for experimentation and development, is conducive to rapid initial development, and exhibits good reproducibility and scalability. Additionally, samples developed using this method generally possess certain degrees of flexibility, strength, and resilience. Their characteristics can be manually adjusted based on the differences in the proportions of each component, making them suitable for a wider range of product applications. Thirdly, the basic formula is composed of biopolymers, plasticisers, solvents, and other raw materials, and each component can be fully biodegradable [25]. Films developed on this basis have been proven to effectively biodegrade in natural environments [26]. Ultimately, corn waste powder, gelatin, glycerol, beeswax and water formed the initial structure of the bioplastic in this research. Among them, gelatin and glycerol were both purchased from Taobao (a Chinese e-commerce platform). The gelatin used was Fujiabaili-brand gelatin sheets produced in Shanghai, China, with a content of 90%. Glycerol was sourced from Shengbang Biotechnology Co., Ltd. in Shangqiu City, Henan Province, and in a 250 mL bottled product with a content of 98%. Table 1a displays the formula percentages. The left side, labelled "component", lists all the necessary materials for the final formula, while the right side, labelled "mass", indicates the proportions of different materials in the experiment. Table 1b lists the parameters employed in this experiment, with all materials measured in grams.

Table 1. (**a**): The final proportion of the formula; (**b**): the formulation used in this study.

(a)	
Component	**Mass %**
Corn Waste Powder	6.8%
Glycerol	6.8%
Gelatin	18.2%
Beeswax	4.6%
Water	63.6%
(b)	
Component	**Mass Range (g)**
Corn Waste Powder	15~30 g
Glycerol	10~20 g
Gelatin	20~50 g
Beeswax	0~20 g
Water	140 g

3.2. Material Processing

The collection and processing of materials have been detailed according to Figure 3, which shows the entire creation process, starting from corn waste pre-treatment to the final corn waste biofilm generation. This processing flow chart draws inspiration from the methods used by Bátori [27], Gustafsson [28], and Yaradoddi [21]. A common aspect of their research is the use of crop residues, which are pulverised, and mixed with plasticisers and other ingredients to produce biofilms. Therefore, considering feasibility, convenience, and other factors, the formulation design was ultimately based on the foundation of these three articles.

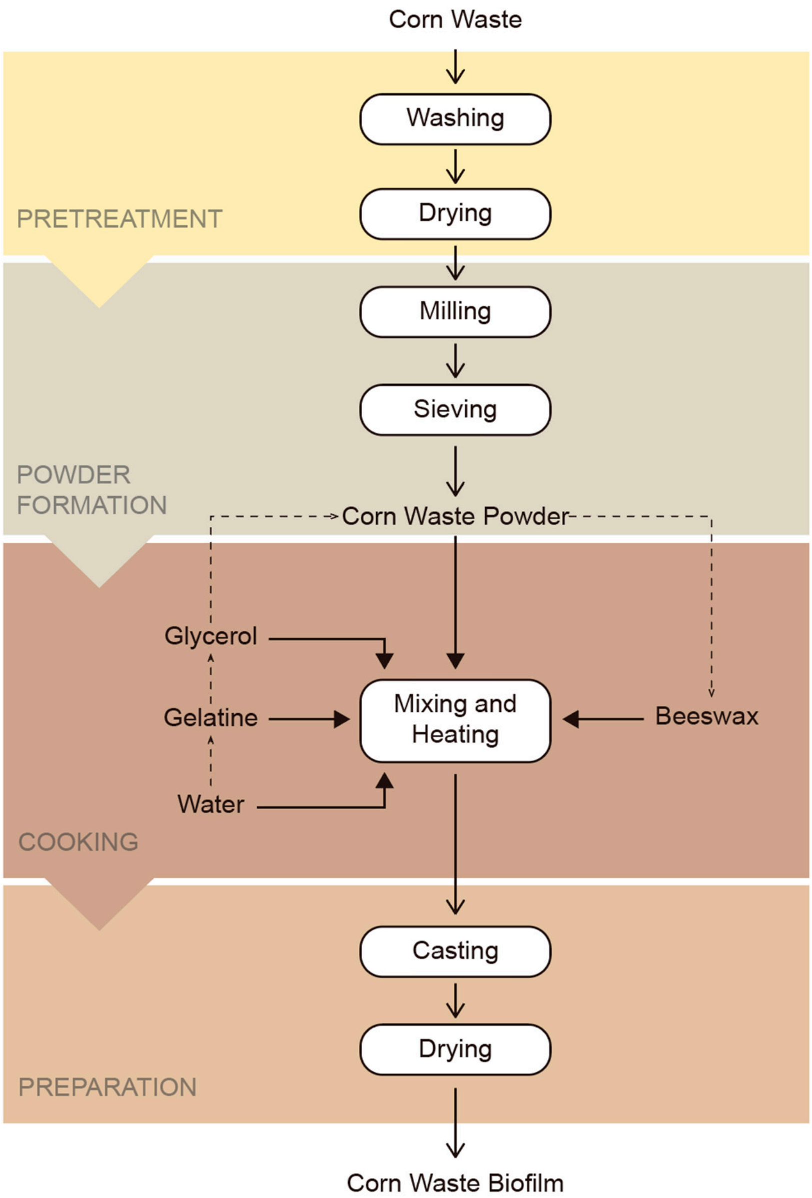


Figure 3. The processing flow chart; dotted lines with arrows indicate the order in which ingredients are added.

Here, the entire process was divided into two major parts for explanation. The first part is the "corn stover handling process". The corn crop residue was obtained in the selected area (located in Shandong Province) in October 2020 and primarily consisted of discarded leaves and straw husks. Figure 4a illustrates the state of corn stover in the fields. It was then collected through the steps shown in Figure 4b. Next, impurities like dust particles, rocks, insects, and other elements that could interfere with experimental data were removed from the corn stover to maintain the uniformity of the raw material's structure. The initially cleaned corn waste was soaked in water for over an hour (Figure 4c) and further washed through manual stirring and friction. The material was washed two or more times until the washing water became clear. After washing, it was spread out in an oven and air-dried at temperatures below 45 degrees Celsius to remove external and internal moisture, preventing waste from deteriorating and minimizing the interference of its moisture with the experimental data. Figure 4d shows the dried corn stover being cut into small pieces and put into a household blender. It was then grounded using a household blender until it became a relatively uniformly mixed powder. Figure 4e depicts the state immediately after being loaded into the mixer, Figure 4f shows the mixer in operation, Figure 4g illustrates the result after grinding (20 min), and Figure 4h showcases the outcome after a second grinding. To obtain smaller-diameter particles with a more uniform structure, a 30-mesh (550 μm) sieve was used to sift the powder, obtaining finer and more stable powder material. The blender used here was a small household blender with a capacity of 2500 g, a rotation speed of 35,000 revolutions per minute, and a power of 4.5 kW.

Figure 4. The handling process of corn stover: (**a**) corn stalks in original state, (**b**) initial material collection, (**c**) filtering and cleaning, (**d**–**h**) grinding process.

As for the production of biomaterial films, it was divided into eight steps, as shown in Figure 5. Figure 5a shows all required tools. First, 140 g of water was added to a container and heated to about 60 °C (Figure 5b). The temperature was measured using a probe-type long-stem thermometer, calibrated in Celsius as the standard unit. After immersing the thermometer into the solution (without touching the bottom), a 15 s waiting period was observed. Then, in the following order, gelatin (10–40 g) (Figure 5c), glycerin (5–25 g) (Figure 5d), pre-processed corn waste powder (15–60 g) (Figure 5e), and beeswax (5–25 g) were added to prepare a mixture solution. Then, the heating temperature was maintained between 60–80 °C throughout the process, continuously stirring the solution, and waiting for each ingredient to be added once the current solution was thoroughly mixed (Figure 5f). Once the mixture was initially uniform, the solution was heated to 100 °C, and maintained at a boiling state for 1–2 min until no obvious particles were visible to the naked eye, and then bubbles and foam were removed by vibrating the container several times. The processed mixture solution was then poured into culture dishes and square moulds. Culture dish samples were used for preliminary sample observations, while square mould materials were used for subsequent material performance tests. When pouring the processed mixture solution into the moulds and culture dishes along the edges, the mould was evenly tilted to ensure that the solution flowed and spread smoothly, controlling the thickness to be around 0.5 mm (Figure 5g). Then, the culture dishes and moulds were placed in a drying oven at below 30 degrees Celsius for drying for about 20 min (Figure 5h). When the dry film could be separated, it was gently pulled down with tweezers to remove it from the bottom of the mould and then placed in an open space for about 24 to 48 h to ensure that the material was fully stable. The processing method mainly used heat condensation, and no difficult-to-dispose chemicals were added in order to minimise pollution to the environment as much as possible throughout the entire process [24–29].

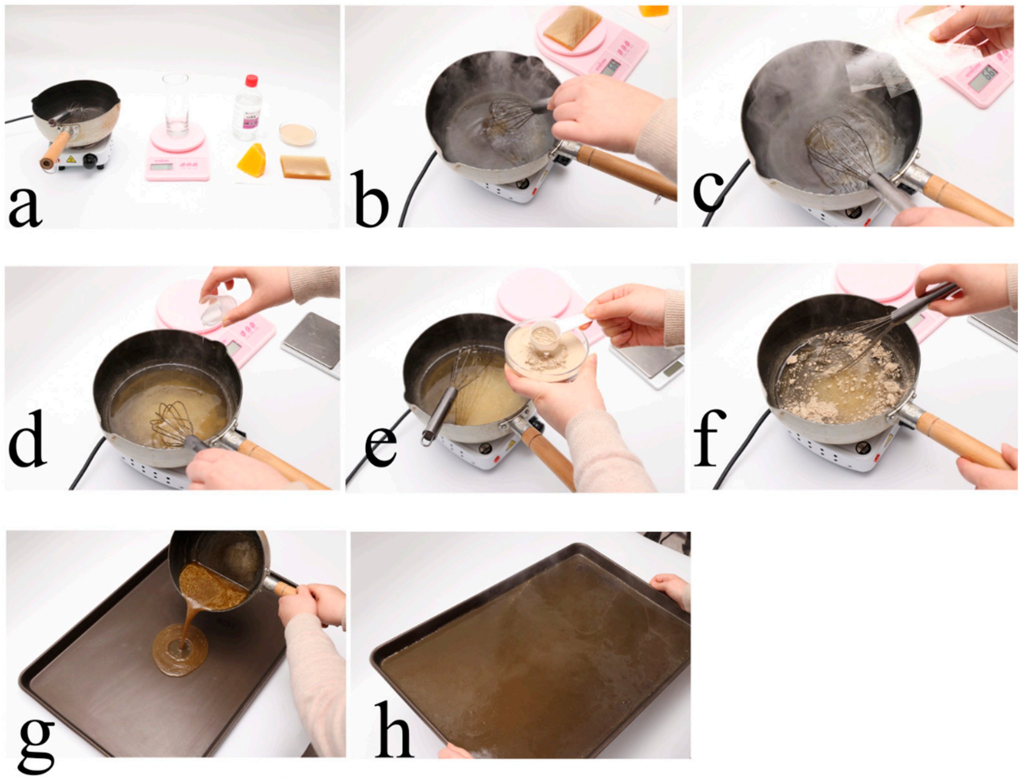


Figure 5. The handling process: (**a**) basic tools, (**b**) mixing and heating, (**c**) Adding gelatin, (**d**) adding glycerin, (**e**) adding corn powder, (**f**) continuing to stir until fully dissolved, (**g**) pouring into sheet mould, and (**h**) spreading evenly and allowing to cool and solidify.

After completion, a total of four control experimental groups were designed and implemented, all conducted in indoor conditions with a natural temperature of 12 °C and a relative humidity of 85%. The only quantified factor was 140 g of water, combined with an increasing amount of variable amounts of corn waste powder ingredients. Based on the original open-source ratio, experiments with the following variables were carried out to confirm the differences in the properties of the finished material due to different proportions of raw materials and to select the formula suitable for the target product design (see Table 2). Figure 6 shows the four group samples: on the left is the biomaterial film in the making, and on the right is a comparative view after processing.

Table 2. Compositions of prepared biomaterials.

Sample		Corn Waste Powder	Glycerol	Gelatin	Beeswax	Water
		Weight (in Grams)				
Group1	S1.1	15	15	40	10	140
	S1.2	30	15	40	10	140
	S1.3	45	15	40	10	140
	S1.4	60	15	40	10	140
Group2	S2.1	15	5	40	10	140
	S2.2	15	10	40	10	140
	S2.3	15	15	40	10	140
	S2.4	15	20	40	10	140
	S2.5	15	25	40	10	140
Group3	S3.1	15	15	10	10	140
	S3.2	15	15	20	10	140
	S3.3	15	15	30	10	140
	S3.4	15	15	40	10	140
	S3.5	15	15	50	10	140
Group4	S4.1	15	15	40	5	140
	S4.2	15	15	40	10	140
	S4.3	15	15	40	15	140
	S4.4	15	15	40	20	140
	S4.5	15	15	40	25	140

Figure 6. Partial samples: the two images display different effects achieved by adding powder of varying concentrations (the colour from dark to light represents the quantity of corn waste powder added from a high to low concentration); **Left** image: the original shapes of films with different corn waste powder concentrations; **Right** image: a comparative view of the films after processing (trimming).

3.3. Primary Feature Test Methods

After two months of experiments, sustainable packaging materials based on corn stover waste were produced and tested. After several comparative experiments and control variable experiments, the final formula ratio was determined as 6.8% corn waste powder, 6.8% glycerin, 18.2% gelatin, 4.6% beeswax, and 63.6% water. Based on this formula, the corresponding material features were further tested. The test content mainly includes three parts, which are Transparency and Colourability (test method and process in Section 3.3.1, results in Section 4.1.1), Strength and Elasticity (test method and process in Section 3.3.2, results in Section 4.1.2), and Smoothness and Waterproofing (test method and process in Section 3.3.3, results in Section 4.1.3).

The whole process was intended to be realised in a relatively fair environment, but due to limitations in funds and equipment, the testing criteria did not have fixed standards to meet; rather, the experiments explored for the optimal states of various variables.

3.3.1. Transparency and Colourability

The test of Transparency and Colourability was primarily conducted through visual observation. During the test, grey paper (C25M16Y16K0) was placed on a white plane to simulate the product inside the packaging. The film was then covered on top for observation (Figure 7). The transparency levels were set as "high", "medium", and "low" based on the clarity displayed by the grey paper: (1) low transparency: the outline pattern of the covered paper sheet cannot be observed through the material sample; (2) medium transparency: the outline of the covered paper sheet is relatively clear; (3) high transparency: the texture characteristics of the covered paper sheet, in addition to the outline, can be clearly observed.

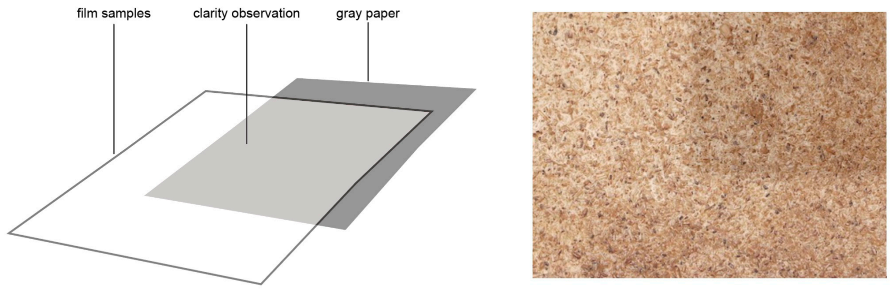


Figure 7. The grey paper was covered under a film to observe the visual state (**left**: sketch map; **right**: real effect).

In terms of dyeing properties, this material was also proven to exhibit favourable colouring characteristics. As shown in Figure 8, the colour testing method involved visual observation, categorizing colour saturation into three levels: (1) Low colourability: the biomaterial sample's inherent colour dominates, with low saturation; (2) Medium colourability: moderate; (3) High colourability: pigment colour dominates, with high saturation. The formula ratio data from repeated transparency tests were used to select red, yellow, and green for the colour saturation test. To avoid changes in pigment properties due to prolonged high temperatures, the dyeing process was conducted after the mixed solution was boiled. It is worth noting that the experimental process in this study did not include chemical treatment or secondary screening of waste materials. The detailed values of Low/Medium/High saturation are discussed with the experiments in the results section.

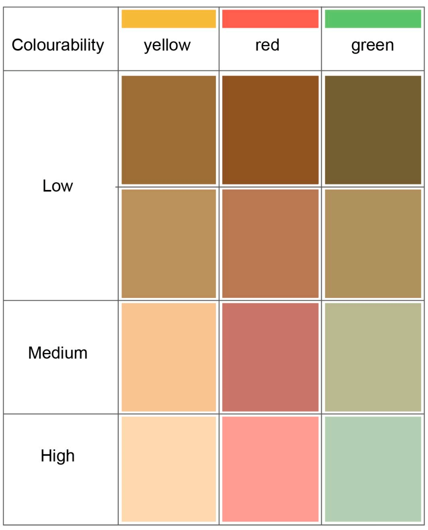


Figure 8. Visual state of red, yellow, and green samples at different levels of colour rendering.

3.3.2. Strength and Elasticity

In the test of Strength and Elasticity, the strength and elasticity of the biomaterial film are related to the content of gelatin and glycerin. Gelatin, a gel-like substance extracted from animal proteins, is commonly used as an adhesive in the production of biomaterials [13]. In this study, to achieve a uniform distribution of the material, the corn waste material mixed from straw and leaves was crushed into very small powder particles. A large number of original plant fibres of corn were broken, so there is a huge need to use gelatin for adhesive. Meanwhile, the role of glycerin is to act as a binder to maintain the bonds of molecules in biomaterials, which is particularly critical in the process of film preparation [16,30]. Insufficient glycerin can make the biomaterial brittle, difficult to de-mould, and prone to fracture, while excessive glycerin can make the material too stretchable, easily breaking the limit of gelatin adhesion and causing the biofilm to rupture [31]. Therefore, during material testing, the ratio of gelatin to glycerin was one of the key test contents. Here, the elasticity test was conducted by one female author manually folding the biomaterial samples with both hands, pressing down on the centre of the sample, and maintaining the pressure for 3 s. Subsequently, the hands were raised to observe the material's deformation state within 60 s (Figure 9). The elasticity levels were quantified and evaluated based on the performance of the material in its original state: (1) Low elasticity: does not rebound (return to its original shape) after folding; (2) Medium elasticity: rebounds after the pressure is released, with noticeable marks at the folding point, and the crease limits the extent of rebound; (3) High elasticity: rebounds after the pressure is released, and when laid flat again, there are no noticeable deformation marks at the folding point.

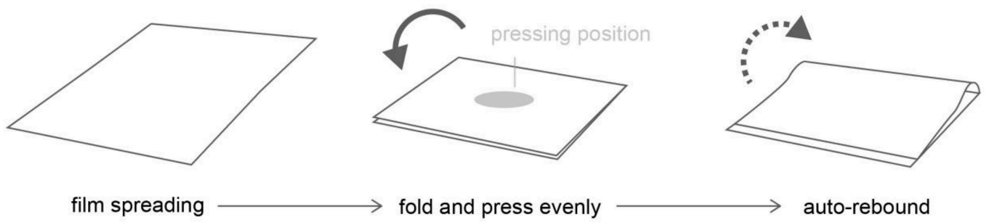


Figure 9. Three steps of the elasticity test method; the line and arrow in the upper left corner of the middle picture represents the direction when fold and press, and the dotted arrow in the right picture represents the path of the material's automatic rebound.

This study referenced the determination of the stretch properties of plastic films to be less than 1 mm (based on the international standard ISO1184-1983 [32]). Tensile tests were conducted on the film samples, excluding S2.1 and S3.1, which fractured during the elasticity test, to confirm the tensile strength and deformation performances under different formulations. As this test does not involve specialised instruments, manual stretching force was used instead of a tensile testing machine. As shown in Figure 10, based on the international standard mentioned before, an experimental biomaterial with a thickness of 0.5 mm was uniformly cut into a dumbbell-shaped strip measuring 20 mm $\times$ 150 mm, with neat edges. Ink was used to mark the centre point of the strip at 25 mm on either side. Subsequently, with hands replacing the testing machine to grip the sample to hold flat, avoiding sliding, stress was applied steadily to simulate external stretching. Due to the limited pulling force of a person, this method is not suitable for continuously applying tension until all samples fracture, and then calculating the maximum tensile force to define tensile strength. Next, the samples were manually stretched to the limit position (human-driven stretching limit) and maintained for 15 s as a constant value. The choice of 15 s here was based on the physical condition of the tester. The degrees of change in the state of the samples during this stage were recorded instead of using precise instruments to measure in MPa. As shown in Figure 11, this experiment categorised the tensile strength of these samples into the following three levels: (1) Low tensile strength: the sample tears during steady stretching or within the 15 s after reaching maximum force; (2) Medium tensile strength: the sample does not tear during the test, and the deformation distance between the gauge marks increases by less than 5% compared to the original distance (50 mm); (3) High tensile strength: the sample does not tear during the test, and the deformation distance between the gauge marks increases by more than 5% compared to the original distance (50 mm).

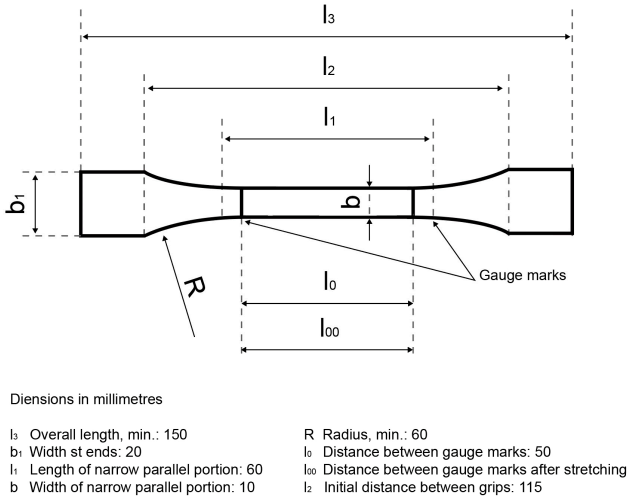


Figure 10. Strength test specific values.

Formula	Tensile Strength		
	Low	Medium	High
$\frac{l_{00} - l_0}{l_0}$ (%)	Sample breaks during test	< 5%	5% <

Figure 11. Criteria for classifying strength grades.

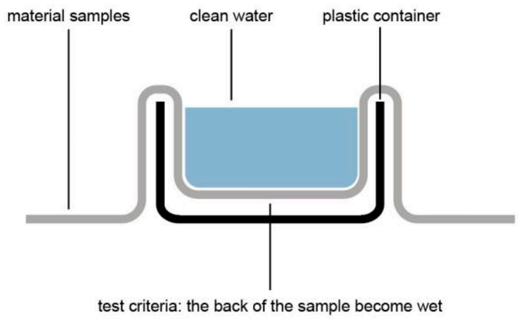
3.3.3. Smoothness and Waterproofing

Smoothness refers to the smooth or matte effect presented by the material on the surface. The smoothness of the biomaterial film depends on the beeswax component used in the manufacturing process. Without adding beeswax, the biofilm will present a shiny and transparent visual characteristic, and the touch of the surface is also very smooth. The addition of beeswax can give the material a frosted texture, adding a subtle visual feature and making it have a wider application potential [21].

For the Smoothness and Waterproofing test, a combination of visual observation and tactile observation were used to categorise the smoothness of the material into three levels: (1) Low smoothness: the biofilm surface exhibits an obvious granular matte characteristic, rough to the touch, and the matte texture obscures the contours of objects behind it, making the contours unclear; (2) Medium smoothness: the biofilm surface shows a slightly rough matte characteristic, with some matte feel upon touch, and the contours of objects covered behind it are relatively clear; (3) High smoothness: the biofilm, when laid flat, exhibits a glossy texture with reflective properties and a smooth touch.

The addition of beeswax can effectively reduce the inherent porosity of the material to some extent, improving the film's waterproofing. However, as this study has not yet delved into the research of fully bio-based waterproof coatings, waterproofing coating experiments have not been conducted at this stage. Thus, the waterproof performance of this biomaterial is limited and currently does not reach the complete waterproof level of polyethylene plastic. Nevertheless, a simple waterproof test was still conducted to explore the current performance of the biofilm.

S4 was chosen for the waterproofing because beeswax can enhance the waterproofing of the film to some extent, and the S4 experiment had varying beeswax content as the only variable, allowing for a comparison of the impact of beeswax content on waterproofing. As show in Figure 12, four samples, S4.1 to S4.4, were cut into square pieces of 100 × 100 mm and placed on a bottle cap-shaped plastic container with a diameter of 30 mm and a depth of 13 mm. A total of 5 mL of water was dripped onto the samples from the top, and the impact of water immersion on the material was observed visually. The time points after 10 min, 20 min, and 30 min of soaking were set as nodes, and at each node, the sample was lifted to observe whether the back of the sample started to appear wet. If wetness was observed, it was defined as 'leaking'. Different leaking phenomena occurring at 10 min, 20 min, and 30 min were respectively defined as low, medium, and high waterproofing.



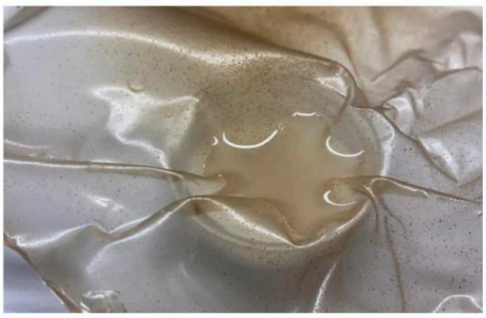


Figure 12. Above: Schematic of waterproof test; **Below**: Real picture of waterproof test.

4. Results

4.1. Material Characteristics

4.1.1. Transparency and Colourability

It was found through group 1 of experiments that the transparency is directly related to the proportion of corn waste powder. The crushed corn waste powder presents a granular form in the material. In corn waste, lignin is a natural adhesive that shapes the fibrous structure of wood and is present in various cellulose-rich materials [6]. When mixed with water and heated at high temperature (because the mixture in cooking is primarily water, the cooking temperature should be 100 °C), the lignin chains break, releasing a liquor-like substance [9,30], which darkens the colour of the mixture and affects the colour and transparency of the final product.

Before blending, corn waste was washed and sifted with clean water and NaOH. Under the influence of high temperature, most of the black pigments were filtered out, and the fibres largely lost their inherent colour [10,33], becoming more transparent. On this basis, the mixture ratio of corn waste and water could be adjusted, effectively reducing water usage. However, this may involve the use of chemical solvents, and whether it would impact the material's harmless degradation is yet to be confirmed. Therefore, this study did not adopt this method.

Firstly, the content of corn waste powder was limited to 15–30 g with a water ratio of 10.5–21%. When the densities of the remaining components were the same, the material samples were categorised as 'medium'. This indicates noticeable semi-transparent characteristics, where the paper's outline is relatively visible, as shown in the first row of Figure 13 with samples like Sample 1 and Sample 2. In Sample 1, 21:100 represents the ratio of corn waste powder to water, and the others follow the same pattern. Maintaining semi-transparent characteristics can be advantageous for light-shielding and heat-avoidance, making it more friendly for preserving internal products as packaging [31]. At the same time, a certain degree of transparency can aid in recognizing internal packaged products, enhancing the packaging's quality for effective commercial purposes [33]. Secondly, when the proportion of corn waste powder exceeded 30 g, the film appeared darker and had a stronger opacity, and the grey paper behind it could not be recognised. The transparency exhibited by the samples under these conditions was considered 'low'. Thirdly, if the corn waste powder in the formula was below 15 g, it went beyond the specified range. Although the transparency may have been 'higher', it would have compromised the physical properties and utility value of the film. Therefore, this study did not further explore these cases.

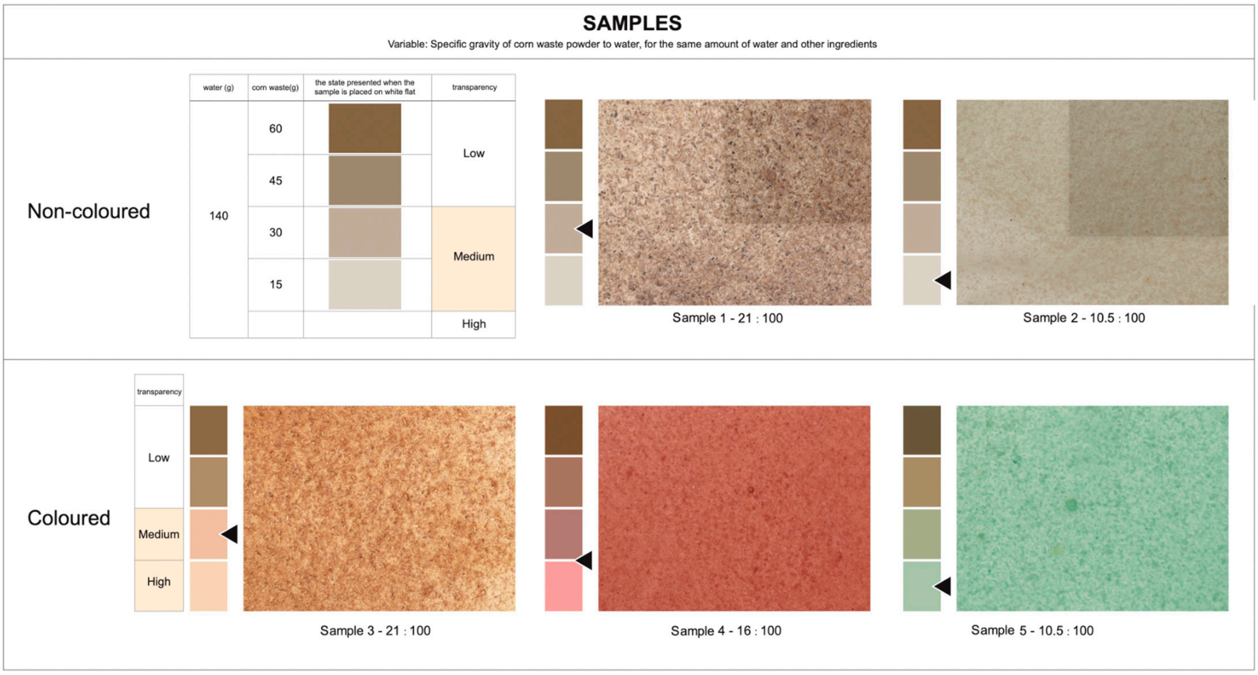


Figure 13. Comparing test samples to analyse transparency and colourability: first row: transparency experiment, second row: coloured experiment.

Regarding the colourability, natural pigment juice extracted from carrots was purified using a water extraction method [34]. Using a test tube, the purified juice was gradually dripped into the moderately coloured Sample 1 formula while continuously stirring to achieve uniform colouring. The solution underwent an evident colour change after approximately 5 drops (about 0.5 g). The dyed solution was then spread and cooled, resulting in the coloured Sample 3. Subsequently, the pigments were quantified for this study. In the same manner, red and green pigment juices were separately extracted from beets and spinach and added to other samples (5 drops each), presenting the effects as shown in the second row of Figure 13. In this experiment, the materials' brownish colour was essentially maintained when the solution was below 5 drops. When the solution exceeded 5 drops, especially in the range of 8–15 drops, the material exhibited vivid and highly saturated characteristics, with the colour of the corn waste itself not distinctly apparent. Therefore, the final choice was the formula with 5 drops of colouring, providing a friendly coloration suitable for commercial purposes [9] (see Figure 14; all the samples in this section were put together to show the performance and adjustable flexibility of the material in terms of transparency and colour rendering). One thing worth mentioning is that this experiment did not accurately quantify the specific molar concentration units of the dye solution used. Therefore, based on the characteristics of different commercial dyes, there is still room to adjust the mixture ratio of corn waste and water, which needs further definition according to practical considerations during actual production.

Figure 14. All the samples in this section. (Colour materials: Sample 1—walnut, Sample 2—coffee, Sample 3—orange, Sample 4—mulberry, Sample 5—spinach).

4.1.2. Strength and Elasticity

The experiments conducted on group 2 and group 3 involved controlling the proportions of glycerol and gelatin to verify the impact of the ratio between these two components on the material's elasticity and (tensile) strength. The film edges, uneven due to the flow of the solution during the production process, were trimmed to obtain uniformly thick material samples measuring 200 × 250 mm. The elasticity and strength of the two groups of samples were assessed through bending and tensile experiments (the tensile test used smaller samples). Manual comparisons were made with polyethylene plastic samples of the same size to find suitable component ratios for practical packaging applications. The reason for using polyethylene plastic for horizontal comparisons is that it is one of the most used plastics in daily life, extensively employed in the manufacturing of plastic bags, films, and other products. It serves as a comparison object due to its widespread application, which overlaps with many features of the film developed in this study.

The elasticity is an inevitable aspect to be tested in packaging production as the original materials undergo bending and joining. Through testing, it was found that, except for samples S2.1 and S3.1, which were classified as having low elasticity due to their inability to rebound, the remaining samples exhibited a certain ability to resist folding. Sample S2.1, due to insufficient glycerol content in the formula, exhibited a higher brittleness and poorer deformation ability, with a relatively neat fracture location overlapping with the force trajectory during bending. Additionally, stress whitening occurred at the edge of the biomaterial fracture due to external forces (Figure 15, left). Sample S3.1, on the other hand, exhibited a poor bonding strength due to insufficient gelatin content, making it prone to large-scale ruptures. The components in the sheet did not adhere to each other, resulting in fine material fragments and powder at the fracture point (Figure 15, right). Samples S2.2 and S3.5 showed characteristics of medium elasticity, with the overall samples being relatively rigid, thus suitable for the outer packaging and transport packaging of products that require a certain resistance to compression. Samples S2.3, S2.4, S2.5, S3.2, S3.3, and S3.4 exhibited high elasticity, closely resembling the physical characteristics of common polyethylene plastic bags, capable of withstanding larger deformation amounts.

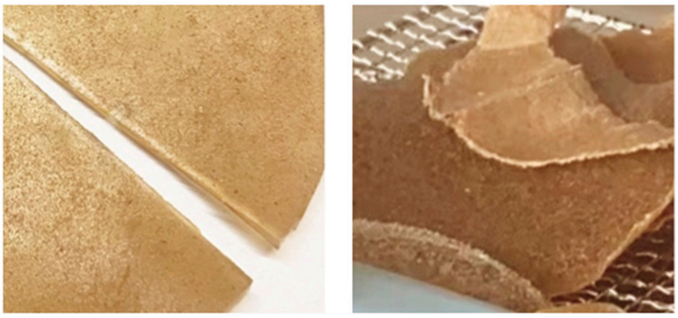


Figure 15. Left: S2.1 biomaterial fracture due to external forces; **Right**: S3.1 fragments and powder at the fracture point.

As shown in Table 3, it was found that, due to the similar density of glycerol and gelatin making the material soft and easily stretchable, samples S2.5 during steady stretching and S3.2 during constant force maintenance, would break the gelatin adhesion limit, resulting in longitudinal tearing. Before tearing, the biomaterial at the fracture point locally thinned due to stretching, showing a distinct whitening characteristic. After the fracture, the material could rebound to some extent, so there was no significant colour and visual difference in the fractured part visually, and the tearing path was relatively free and concentrated in the centre of the sample. S2.2, S2.3, S3.4, and S3.5 showed characteristics of moderate stretching due to the higher density of gelatin and lower density of glycerol. S2.4, S2.5, and S3.3 showed higher stretching levels and did not fracture in this experiment (see Table 2). After the uniform strip sample test, a simple tensile test was also conducted on the initially produced 210 $\times$ 258 mm samples (Figure 16). It was observed that, during the stretching of rectangular samples with similar lengths, the locally thinned lines caused by stress were dispersed, mainly concentrated around the force application point, and the tensile strength was higher, with the lines showing a lighter stretching degree.

This study was primarily reliant on manual and human-controlled processes, inevitably introducing some margin of error. For instance, during the manual laying of samples, small bubbles may have appeared in some biofilms, resulting in a slightly lower strength in these areas compared to other parts of the same material. However, no unexpected factors affecting the overall durability of the product were observed during the experimental process. Additionally, in the tensile test, the inability to maintain tension for an extended period and the limitation of tension applied by a person may lead to the rupture of some samples currently classified as high or medium tensile strengths in longer-duration or higher-force tests. Therefore, to draw scientifical conclusions, further testing using professional instruments is required.

Table 3. Test sample groups' tensile strength values.

Sample	$\frac{I_{00}-I_0}{I_0}$ (%)	Tensile Strength
S2.2	3.2%	Medium
S2.3	4.5%	Medium
S2.4	9.2%	High
S2.5	N/A	Low
S3.2	N/A	Low
S3.3	7.8%	High
S3.4	4.5%	Medium
S3.5	3.7%	Medium

Figure 16. Stretching a rectangular sample of S3.3.

4.1.3. Smoothness and Waterproofing

The proportion of beeswax affects the matte texture of the film, with a higher proportion resulting in a stronger matte feel [35,36]. Considering that the addition of beeswax accelerates the solidification of the mixed solution, an excessive amount of beeswax can lead to overly thick solutions, affecting the smoothness of the spreading process after pouring the solution into the mould, ultimately impacting the uniformity of the film thickness. The purpose of experiment S4 was to verify this biomaterial ratio. After determining the content of other raw materials, 5–25 g of beeswax was added, and the matte texture of the finished product and the smoothness of the spreading process were observed visually. The experiment revealed that sample S4.5, i.e., when the proportion of beeswax in the mixed solution exceeded 9%, the biofilm encountered hindrance during the spreading production process, and the uniformity of the film product was disrupted. In the range of samples S4.1 to S4.2, the solution could spread smoothly in the experimental mould (consistent with the dimensions of the previously used grinding tool, 210 × 258 mm). This indicates that throughout the solution, when the proportion of beeswax is less than 9%, it does not affect the uniformity of the film while presenting a matte texture. In Figure 17, sample S4.4 exhibits a Low smoothness characteristic, with a beeswax content of 20 g, accounting for a high proportion of 9% of the overall solution; sample S4.3 exhibits a Medium smoothness characteristic, with a beeswax content of 15 g, accounting for 6.75% of the overall solution; samples S4.1 and S4.2 exhibit High smoothness characteristics, when the beeswax content was less than 10 g, accounting for less than 4.5% of the overall solution. Since the constant ratio of glycerol to gelatin in this experiment determined the relative softness of the produced material samples, a small packaging was subsequently produced to further observe the visual performance of the materials with different degrees of smoothness when used as packaging for the same item (Figure 18).

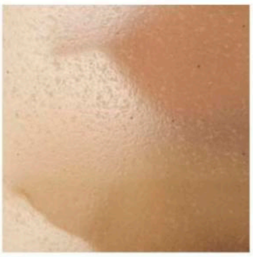
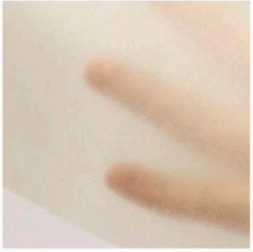
Smoothness	Low	Medium	High
Characterisation			
Sample	S4.4	S4.3	S4.1, S4.2

Figure 17. Biofilm in the three smoothness states of Low, Medium, and High.

Figure 18. Different contents of beeswax in two biofilms. **Left**: Beeswax is 5 g, which accounts for 2.25% of the overall solution (sample S4.1); **Right**: Beeswax is 15 g, which accounts for 6.75% of the overall solution (S4.3).

Within 1 min of contact with water, all four samples experienced varying degrees of softening (Figure 15). S4.1, S4.2, and S4.3 softened after 10 min, to the extent that they broke when lifted and placed back due to gravity. S4.4 also broke after 20 min. Observing and touching the part of the sample soaked in water revealed that the soaked area became soft and fragile, easily torn by external pulling. Irregularly states appeared at the torn areas (a person could easily tear off large pieces), presenting a sticky state when crushed with fingers. The original solid textures of the samples became extremely viscous, while after air-drying, their physical properties returned to the original state. In conclusion, S4.4, with a beeswax content reaching 9% of the overall solution, performed the best and decomposed the slowest when exposed to water. This group was defined as having 'medium waterproofing'. Due to the lack of a waterproof coating on samples, no sample exhibited the characteristics of 'high waterproofing' for the time being. Continuous immersion in water will still accelerate the degradation of this biomaterial. Therefore, more comprehensive experiments are needed in future research to determine relevant waterproof values and explore the integration with bio-based waterproof coatings.

4.2. Packaging Design Applications

After the preliminary biomaterial creation and research, a biofilm was created and used as raw material for a sustainable packaging design. It is semi-transparent, durable, not easy to break, and has a certain degree of waterproof qualities. Hence, a proposal to make disposable packaging bags for urban agricultural goods delivery using the developed material was proposed. It not only generated the application of a circular economy through waste usage and reuse, but also achieved a design process that can significantly reduce the consumption and production of traditional packaging [17,37].

The structure of traditional delivery packaging is a very simple form, generally cut-type flat materials. To protect the internal goods, it is usually folded to form a support structure, and then fixed and sealed by inserting or heat sealing. For harder products, it can be sealed directly without fixing the external shape [18,38]. In this process, the heat sealing of biomaterial film can easily produce toxic substances [39,40]. However, at a production level, the developed biomaterial is more environmentally friendly in the processing process due to the complete use of biological materials; it can be stably bonded via heat sealing like a biomaterial film, while also avoiding the generation of polluting gases.

Therefore, two new packaging proposals based on common structures have been put forward, both of which are fixed and sealed via heat sealing. For larger-sized packaging bags with wider applicability, thicker materials are used to match the protective isolation function during transportation. The experimental material was proven to have good dyeability, but it was not proven to be stably sprayed or printed, so recycled paper tags were attached at the top to distinguish the contents. Small packaging is used only for isolating products inside the large packaging bag, as it is thinner and softer (Figure 19). Apart from the experimental material and recycled paper tags, from the recycling perspective, the entire packaging no longer contains any other substances, which can maximise its harmless composting degradability while saving costs.

Figure 19. Product pictures in two different forms.

The obtained biomaterial is not only an element that can recycle organic matter that is already in a waste state, but also linked to the ability to integrate methods aimed at reducing production impact, simplifying production, and reducing development steps [41].

As for a size diagram, Figure 20 displays information about the packaging dimensions of the visualised effect. In practical applications, this packaging can accommodate products weighing up to 500 g. However, there are many factors that can influence the load-bearing capacity, such as transportation. Therefore, further research in this area can continue to explore applications under various conditions. Figure 17 shows two forms of packaging effect images.

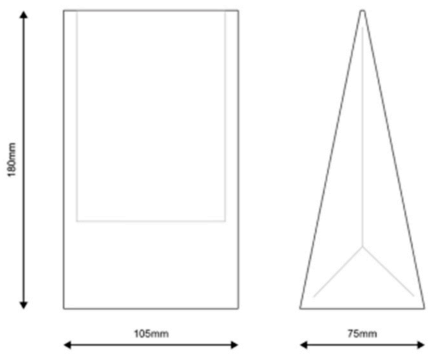


Figure 20. Package size diagram.

4.3. Recycling and Reuse

The entire packaging material design process and all utilised materials prioritise eco-friendliness, aiming to increase the utilization rate or degradation efficiency. Under this modus operandi, supported by demonstrated advantages for distributed production and sustainable regional transformation, a regional waste recycling system targeting agricultural economies could potentially be established. From the collection of agricultural waste, then processed into distribution packaging and transported to consumers, and then once the packaging is discarded, that can be recycled into compost to supports crop growth. Figure 21 shows the whole process of corn stover's growth, regeneration, and recycling processes.

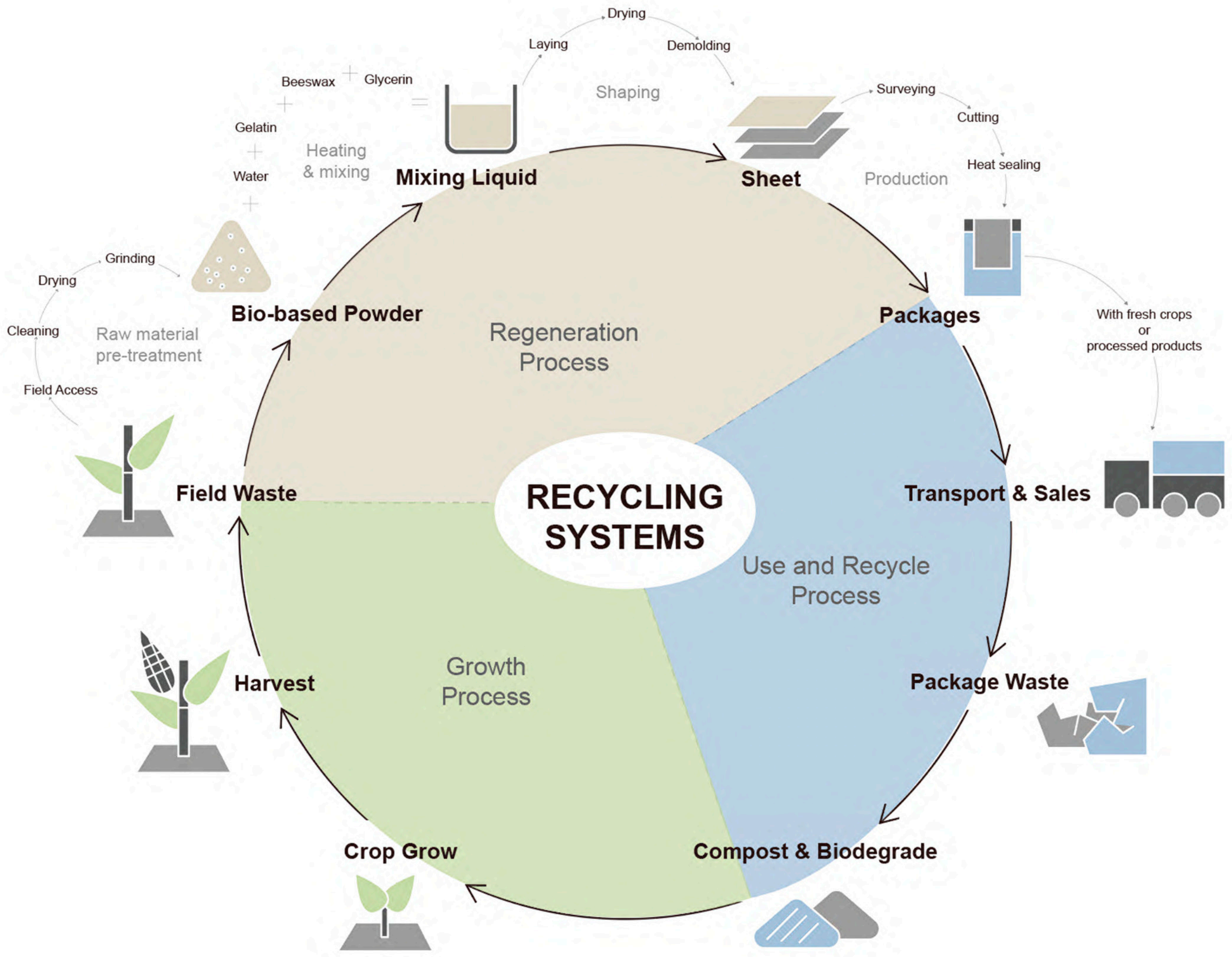


Figure 21. The flow chart of the whole corn stover design process.

5. Discussion

Through biomaterial experimentation, this study showcased the feasibility of sustainable material regeneration from agricultural waste, focusing specifically on corn waste as a prime example. This exploration opened up avenues for the repurposing of agricultural waste. While the study established an optimized formula through experimentation, there remains room for further investigation into varying proportions. This exploration aims to create biomaterial sheets with diverse properties suitable for a wider array of applications. The potential ranges of proportions could serve as templates within open-source formulas, facilitating the development of additional plant waste materials.

To promote the application of bio-based and bio-manufactured materials in practical fields and expedite the sustainable processing of agricultural residues, this paper suggests exploring material properties and designing new products from a regional viewpoint [42]. It introduces an approach that complements the well-accepted concept of sustainable recycling from waste to raw materials and emphasises a shift in design practices. This approach, situated at the convergence of design, materials science, biology, and manufacturing, redefines the designer's role as an active producer of materials rather than a passive recipient [8]. It focuses on the designer's perspective and employs a territorial approach, establishing connections between sustainable raw materials, experimental techniques, production methods, and product design [43,44].

This study focused on agricultural waste as its research subject, exploring opportunities for the regeneration of agricultural waste into packaging products, aiming to contribute to the sustainable development of the region. By examining recycling resources and setting development goals from the perspective of regional industries, the research aimed to further promote regional sustainability and facilitate the transition toward a circular economy.

In this approach, it standardised the material testing process according to the necessary material characteristics of the target product and qualified the experimental results. While this method may not be flexible, it can serve as an initial framework for the life cycle of biomaterials and provide possibilities for establishing healthy sustainable development relationships in the local area [45].

However, this study still has certain limitations. One concern is the waterproofing test. Even though it was tested, the detailed waterproof values are not given. Also, the natural environmental humidity may interfere with the biofilm's hardness properties. Importantly, although this biofilm has been proven to be completely compostable based on the referenced open-source formula, specific information about the duration of the cycle still needs to be clarified. Rigorous life cycle analyses and ecological carbon footprint data of the design product need to be clearly observed and recorded to compare with current waste disposal methods and identify points of improvement based on these data. There are also more opportunities to optimise this experimental formula. In the current experiment, apart from the corn waste and natural pigments, the remaining additives were commercial products. The composition of the original "waste" in the entire formula occupied a small proportion, and other raw materials still have great potential for source optimisation. For example, gelatin used as an adhesive is extracted from animal proteins, but according to research, a similar type of adhesive can also be extracted from potato waste starch [46].

6. Conclusions

This study concentrates on utilizing the agricultural waste of corn stover as the main material from Shandong Province to develop a cost-effective, efficient, and practical method for a packaging design. The outcome, a biomaterial-based film, not only fulfils the need for packaging agricultural products but also establishes a pathway for a sustainable local production and sales cycle by repurposing waste materials effectively.

The formula developed in this study is cost-effective, with a straightforward operational process. The process involved comparative experiments analysing moisture content and analysing aspects like the smoothness and colour of the final product. Finally, application tests for the biofilm were conducted. Throughout the entire testing process, the formulation was continuously optimised, and experiences were consistently summarised. The resulting biofilm now possesses high practical value.

In conclusion, this research linked biomaterial characteristics with regional identity and broadens the scope of sustainable material design to a novel perspective. Future advancements necessitate more systematic tools and methods for structuring and regulating material formula composition ratios, particularly concerning their application in the packaging design. Converting agricultural waste into raw materials for designing an agricultural product packaging, thereby establishing a sustainable cyclical system, stands out as a promising avenue for future research in agricultural product material packaging and fostering the establishment of a sustainable cyclical system.

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References

1. World Bank. *Agriculture, Forestry, and Fishing, Value Added (% of GDP)—China*; World Bank: Washington, DC, USA, 2022. Available online: https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=CN (accessed on 30 December 2022).
2. Rojas, C.; Cea, M.; Iriarte, A.; Valdés, G.; Navia, R.; Cárdenas-R, J.P. Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings. *Sustain. Mater. Technol.* **2019**, *20*, e00102. [CrossRef]
3. Wang, P.; Chen, Y.M.; Wang, Y.; Lee, Y.Y.; Zong, W.; Taylor, S.; McDonald, T.; Wang, Y. Towards comprehensive lignocellulosic biomass utilization for bioenergy production: Efficient biobutanol production from acetic acid pretreated switchgrass with Clostridium saccharoperbutylacetonicum N1-4. *Appl. Energy* **2019**, *236*, 551–559. [CrossRef]
4. Opoku-Kwanowaa, Y.; Wu, J.; Chen, X.; Sharaf, A.; Attipoe, S.G. Soil Physicochemical Properties Variation in Black Soil after the Long-term Application of Different Organic Amendments. *Asian J. Adv. Agric. Res.* **2020**, *12*, 24–34. [CrossRef]
5. Raheem, A.; Ding, L.; He, Q.; Mangi, F.H.; Khand, Z.H.; Sajid, M.; Ryzhkov, A.; Yu, G. Effective pretreatment of corn straw biomass using hydrothermal carbonization for co-gasification with coal: Response surface Methodology–Box Behnken design. *Fuel* **2022**, *324*, 124544. [CrossRef]
6. Moshood, T.D.; Nawanir, G.; Mahmud, F.; Mohamad, F.; Ahmad, M.H.; AbdulGhani, A. Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100273. [CrossRef]
7. Chong, T.Y.; Law, M.C.; Chan, Y.S. The Potentials of Corn Waste Lignocellulosic Fibre as an Improved Reinforced Bioplastic Composites. *J. Polym. Environ.* **2021**, *29*, 363–381. [CrossRef]
8. Ishangulyyev, R.; Kim, S.; Lee, S.H. Understanding Food Loss and Waste-Why Are We Losing and Wasting Food? *Foods* **2019**, *8*, 297. [CrossRef]
9. Meadowcroft, J. Who is in Charge here? Governance for Sustainable Development in a Complex World. *J. Environ. Policy Plan.* **2007**, *9*, 299–314. [CrossRef]
10. El Haggar, S. *Sustainable Industrial Design and Waste Management: Cradle-To-Cradle for Sustainable Development*; Academic Press: Cambridge, MA, USA, 2007.
11. Sharma, A.; Kumar, V.; Shahzad, B.; Tanveer, M.; Sidhu, G.P.S.; Handa, N.; Kohli, S.K.; Yadav, P.; Bali, A.S.; Parihar, R.D.; et al. Worldwide pesticide usage and its impacts on ecosystem. *SN Appl. Sci.* **2019**, *1*, 1446. [CrossRef]
12. Reshmy, R.; Philip, E.; Madhavan, A.; Sindhu, R.; Pugazhendhi, A.; Binod, P.; Sirohi, R.; Awasthi, M.K.; Tarafdar, A.; Pandey, A. Advanced biomaterials for sustainable applications in the food industry: Updates and challenges. *Environ. Pollut.* **2021**, *283*, 117071.
13. Østergaard, P.A.; Duic, N.; Noorollahi, Y.; Mikulcic, H.; Kalogirou, S. Sustainable development using renewable energy technology. *Renew. Energy* **2020**, *146*, 2430–2437. [CrossRef]
14. Kumar Gupta, G.; De, S.; Franco, A.; Balu, A.M.; Luque, R. Sustainable biomaterials: Current trends, challenges and applications. *Molecules* **2015**, *21*, 48. [CrossRef] [PubMed]
15. Milios, L. Advancing to a Circular Economy: Three essential ingredients for a comprehensive policy mix. *Sustain. Sci.* **2018**, *13*, 861–878. [CrossRef] [PubMed]
16. Rujnić-Sokele, M.; Pilipović, A. Challenges and opportunities of biodegradable plastics: A mini review. *Waste Manag. Res.* **2017**, *35*, 132–140. [CrossRef] [PubMed]
17. LinkedIn Corporation. *Biomaterials Market Growth Share 2022 with Industry Size, Business Opportunities, Key Drivers, Market Performance, Development and Dynamics, Major Key*; LinkedIn Corporation: Sunnyvale, CA, USA, 2022.
18. Wang, W.; Mo, T.; Wang, Y. Better self and better us: Exploring the individual and collective motivations for China's Generation Z consumers to reduce plastic pollution. *Resour. Conserv. Recycl.* **2022**, *179*, 106111. [CrossRef]
19. Precedence Research. Biomaterials Market Size, Share & Growth Analysis Report by Product (Metallic, Ceramics, Natural, and Polymers). Available online: https://www.precedenceresearch.com/biomaterials-market (accessed on 23 November 2023).
20. Pascoli, D.U.; Dichiara, A.; Gustafson, R.; Bura, R. A Robust Process to Produce Lignocellulosic Nanofibers from Corn Stover, Reed Canary Grass, and Industrial Hemp. *Polymers* **2023**, *15*, 937. [CrossRef] [PubMed]

21. Oliveira, V.R.L.; Santos, F.K.G.; Leite, R.H.L.; Aroucha, E.M.M.; Silva, K.N.O. Use of biopolymeric coating hydrophobized with beeswax in post-harvest conservation of guavas. *Food Chem.* **2018**, *259*, 55–64. [CrossRef] [PubMed]
22. Arif, Z.U.; Khalid, M.Y.; Sheikh, M.F.; Zolfagharian, A.; Bodaghi, M. Biopolymeric sustainable materials and their emerging applications. *J. Environ. Chem. Eng.* **2022**, *10*, 108159. [CrossRef]
23. Zhang, L.; Liu, Y.; Hao, L. Contributions of open crop straw burning emissions to PM2.5 concentrations in China. *Environ. Res. Lett.* **2016**, *11*, 014014. [CrossRef]
24. Dunne, M. *Bioplastic Cook Book*; FAB Textiles Inc.: Vaughan, ON, Canada, 2018.
25. Wojcieszak, D.; Przybył, J.; Czajkowski, Ł.; Majka, J.; Pawłowski, A. Effects of Harvest Maturity on the Chemical and Energetic Properties of Corn Stover Biomass Combustion. *Materials* **2022**, *15*, 2831. [CrossRef]
26. Rhim, J.W.; Ng, P.K. Natural biopolymer-based nanocomposite films for packaging applications. *Crit. Rev. Food Sci. Nutr.* **2007**, *47*, 411–433. [CrossRef]
27. Gustafsson, J.; Landberg, M.; Bátori, V.; Åkesson, D.; Taherzadeh, M.J.; Zamani, A. Development of Bio-Based Films and 3D Objects from Apple Pomace. *Polymers* **2019**, *11*, 289. [CrossRef]
28. Yaradoddi, J.S.; Banapurmath, N.R.; Ganachari, S.V.; Soudagar, M.E.M.; Sajjan, A.M.; Kamat, S.; Mujtaba, M.A.; Shettar, A.S.; Anqi, A.E.; Safaei, M.R.; et al. Bio-based material from fruit waste of orange peel for industrial applications. *J. Mater. Res. Technol.* **2022**, *17*, 3186–3197. [CrossRef]
29. Kristo, E.; Biliaderis, C.G.; Zampraka, A. Water vapour barrier and tensile properties of composite caseinate-pullulan films: Biopolymer composition effects and impact of beeswax lamination. *Food Chem.* **2007**, *101*, 753–764. [CrossRef]
30. Huang, E.; Zhang, X.; Rodriguez, L.; Khanna, M.; de Jong, S.; Ting, K.C.; Ying, Y.; Lin, T. Multi-objective optimization for sustainable renewable jet fuel production: A case study of corn stover based supply chain system in Midwestern U.S. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109403. [CrossRef]
31. Park, K.E.; Kang, G.H.; Kim, H.I.; Yu, G.J.; Kim, J.T. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. *Energy* **2010**, *35*, 2681–2687. [CrossRef]
32. International Standard ISO 1184:1983(E). Available online: https://cdn.standards.iteh.ai/samples/5774/89c3bab575284993a9801a5b9e2d2128/ISO-1184-1983.pdf (accessed on 1 February 2024).
33. Calva-Estrada, S.J.; Jiménez-Fernández, M.; Lugo-Cervantes, E. Pro-tein-based films: Advances in the development of biomaterials applicable to food packaging. *Food Eng. Rev.* **2019**, *11*, 78–92. [CrossRef]
34. Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.J.; et al. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*; National Renewable Energy Lab.(NREL): Golden, CO, USA, 2011.
35. Reyes, L.F.; Cisneros-Zevallos, L. Degradation kinetics and colour of anthocyanins in aqueous extracts of purple-and red-flesh potatoes (*Solanum tuberosum* L.). *Food Chem.* **2007**, *100*, 885–894. [CrossRef]
36. Amornraksa, S.; Subsaipin, I.; Simasatitkul, L.; Assabumrungrat, S. Systematic design of separation process for bioethanol production from corn stover. *BMC Chem. Eng.* **2020**, *2*, 10. [CrossRef]
37. Hess, J.R.; Kenney, K.L.; Wright, C.T.; Perlack, R.; Turhollow, A. Corn stover availability for biomass conversion: Situation analysis. *Cellulose* **2009**, *16*, 599–619. [CrossRef]
38. Martinez Hernandez, E.; Ng, K.S. Design of biorefinery systems for conversion of corn stover into biofuels using a biorefinery engineering framework. *Clean Technol. Environ. Policy* **2018**, *20*, 1501–1514. [CrossRef]
39. Valdez-Vazquez, I.; Acevedo-Benítez, J.A.; Hernández-Santiago, C. Distribution and potential of bioenergy resources from agricultural activities in Mexico. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2147–2153.
40. Hamilton, L.A.; Feit, S. *Plastic & Climate: The Hidden Costs of a Plastic Planet*; Center for International Environmental Law CIEL: Genève, Switzerland, 2019.
41. Markevičiūtė, Z.; Varžinskas, V. Smart Material Choice: The Importance of Circular Design Strategy Applications for Bio-Based Food Packaging Preproduction and End-of-Life Life Cycle Stages. *Sustainability* **2022**, *14*, 6366. [CrossRef]
42. Moshood, T.; Nawanir, G.; Mahmud, F.; Mohamad, F.; Ahmad, M.; Abdul Ghani, A. Expanding Policy for Biodegradable Plastic Products and Market Dynamics of Bio-Based Plastics: Challenges and Opportunities. *Sustainability* **2021**, *13*, 6170. [CrossRef]
43. Astudillo, Á.; Rubilar, O.; Briceño, G.; Diez, M.C.; Schalchli, H. Advances in Agroindustrial Waste as a Substrate for Obtaining Eco-Friendly Microbial Products. *Sustainability* **2023**, *15*, 3467. [CrossRef]
44. Bátori, V.; Jabbari, M.; Åkesson, D.; Lennartsson, P.R.; Taherzadeh, M.J.; Zamani, A. Production of Pectin-Cellulose Biofilms: A New Approach for Citrus Waste Recycling. *Int. J. Polym. Sci.* **2017**, *2017*, 9732329. [CrossRef]
45. Power, D. *Priority Sector Report: Creative and Cultural Industries*; European Commission; Publications Office of the European Union: Brussels, Belgium, 2011.
46. Hong, J.; Ren, L.; Hong, J.; Xu, C. Environmental impact assessment of corn straw utilization in China. *J. Clean. Prod.* **2016**, *112*, 1700–1708. [CrossRef]