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Synergistic Effects of Natural Binding Agents on the Performance of Agricultural Residue-Based Chemical Free Handmade Paper

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ABSTRACT

Due to environmental concerns and legal constraints, the paper industry has been investigating eco-friendly and sustainable alternatives to synthetic binding agents. Natural binding agents that can improve paper strength and printability while lowering the carbon footprint of the industry include proteins, starch, gums, and cellulose derivatives. Promoting the production of handmade paper from agricultural waste (rice straw and sugarcane bagasse) is the goal of the current project. This experiment uses variable cellulose ratios made from diverse agricultural residues, which changes the production process. The handmade technique, which uses these raw residues in different ratios and analyses the parameters of handmade paper by varying concentrations of natural binding agents (starch, aloe vera, corn flour and gum rosin), is a fairly simple and environmentally safe method used to make craft papers. It is shown that the substances are both economical and environmentally beneficial. This study shows that the sectors that make handmade paper can find sustainable alternatives in agricultural waste. The function of different natural binders, their relative benefits over synthetic binders, and their use in the production of paper are all examined in this study. Among all the handmade paper samples across the different binding agent tables, the **best-performing combination** is observed in the sample using **Binding Agent (Gum rosin)** at **5% concentration** with **Highest tensile strength**: Up to **6.8 kN/m, Highest burst index**: Reaching **6.9 KPa·m²/g, Good GSM values**: Often above **350 g/m², Controlled thickness**: Typically between **1.4–1.9 mm and Lowest absorbency**: As low as **0.5–0.9 g/m².**

Keywords: Sustainable, Cellulose, Natural Binding Agent, Gum Rosin, Waste.

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INTRODUCTION

Chemical binders are used by paper manufacturers all over the world to achieve the desired tensile strength of paper. These binders include vinyl acetate, urea-formaldehyde, acetaldehyde, and acrylamide. Although alternatives to synthetic paper binders have been studied, no renewable binder has yet to be found that can match the strength of the conventional binders. According to [1], plant-based products would be a perfect substitute for the chemicals now utilized in the paper sector. Adhesion and cohesion are the two primary requirements for effective binding that nature has demonstrated. It is crucial that the largest area of substrate is covered and that the binder adheres well to the substrate since bonding strength rises with bonding area. A technical binder should be "fluid" during application to cover as much of the substrate's surface as possible for good cohesion. The binder is then transformed into a solid state by a chemical reaction or by the evaporation of its solvent; in the case of paper coating binders, the solvent is typically water, and the binding process is finished by the evaporation of the water in the drying section. Coatings can be classified as either pigmented or non-pigmented; the former simply entails applying the coating material onto the paper, where it should adhere to the surface once dry. When it comes to pigmented coatings, the binder must perform a greater variety of tasks.The pigment particles must be bound together, the pigment must be bonded to the paper substrate, and the coating mix must have the ideal rheology. Control the coating color's rate of water absorption; enhance specific paper qualities including stiffness and surface strength; regulate the paper sheet's flatness; and regulate ink penetration during later printing processes. The paper industry uses a wide variety of binder types, which can be broadly divided into two categories: natural and synthetic. These are the paper furnish's non-fibrous sections. Mineral matter was added to pulp before sheets were formed in the early days of papermaking to make the paper heavier. Adulteration is the term used to describe this procedure. It was later discovered that adding specific minerals to paper had many advantages. We call these extra minerals fillers. Filling or loading is the term used to describe the actual procedure. When applied in specific amounts, fillers enhance the paper's opacity, tensile strength, burst index, and surface smoothness. As a result, it makes paper more suitable for printing. Clay or kaolin are the most widely used fillers. The sizing agents (starch, gum rosin, aloe vera, and maize flour) constitute another significant class of additives. The paper's size

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prevents liquids, like writing inks, from penetrating it. Writing on unsized paper might not be feasible. Rosin size is the most traditional sizing agent. There are numerous other additions, including wet and dry strength compounds. It is important to remember that pulp by itself does not create paper. Additional elements are required. Rice straw has a high ash concentration, therefore additives are largely unnecessary. Paper sheets made from this basic material have a closed surface, therefore writability can be improved with very minor scaling. In addition to the use of additives, the pulp from agricultural waste must be mixed with other types of pulp, ideally soft wood pulp, to guarantee a fair speed for the paper machine and to make up for some paper flaws [2] .

PULP AND PAPER MANUFACTURING HISTORICAL TREND

In Egypt, papyrus has been used as a non-wood plant fiber for papermaking since 3000 BC. In AD 105, papermaking was actually found in China, where sheets were made from mulberry and hemp rag fibers [3,4,5]. The craft of papermaking spread widely during the ensuing centuries, from China Turkestan in the west to Siam (present-day Thailand) in the south and Japan in the east. The Arabs learnt how to make handmade paper in Turkestan in 751 AD, and they carried it westward along their trading routes. Samarkand, Baghdad (793 AD), Damascus, Cairo (900 AD), and Fez (1100 AD) were among the places where papermaking advanced. It then made its way to Spain in 1151 AD, France in 1348 AD, and finally Germany in 1390 AD [6,7]. The invention of printing by moveable sort in Germany in 1450 led to a significant drop in the cost of producing books. Because of this, there was a need for printing surfaces that parchment would not be able to supply. Mills for hand-making paper were constructed in almost every European nation over the course of the following 150 years [8]. After this period, rags and old ropes were no longer sufficient to meet the resulting surge in demand. Thus, the demand for substitute raw materials grew more intense. Today, the developing market economies of Asia, Africa, and Latin America have the highest ratio of non-wood to total pulping capacities for papermaking, and the pulping capacity of non-wood plant fibers is increasing at a faster rate globally than the volume of wood pulp [9].

MANUFACTURING PAPER USING DIFFERENT NATURAL BINDERS

- **Starch**

Due to its functional qualities and environmental advantages, starch a biodegradable and renewable polymer has been extensively investigated as a natural binder in the production

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of paper. Made up of glucose units, starch is a polysaccharide that is obtained from plants like corn, potatoes, and tapioca. Because it can create strong connections with cellulose fibers, it is the perfect natural adhesive for making paper. Because they are inexpensive, environmentally friendly, and sustainable, starch-based binders are becoming more and more popular than synthetic ones. Hydroxyl groups make form the chemical structure of starch and are essential to its binding capabilities. By facilitating hydrogen bonding with cellulose fibers, these hydroxyl groups increase the paper's mechanical strength. However, chemical changes can be used to alleviate the limitations of native starch, such as its low water resistance and high water solubility[10]. It has been demonstrated that cationic starches greatly increase the tensile and burst strength of paper. For example, compared to traditional additives, the addition of cationic starch to bagasse pulp increased its tensile strength by 63% and its burst strength by 37% [11].

- **Aloe Vera**

Because of its special qualities, aloe vera has been investigated as a binder in a variety of applications, including the production of handmade paper. Its inherent adhesive characteristics, biocompatibility, and capacity to improve mechanical properties are the main reasons for its usage as a binder. Aloe vera's use in related applications, like cigarette paper and ceramic compacts, where it enhances structural integrity and functional qualities, helps explain its importance in papermaking. Aloe vera gel has the potential to improve the mechanical qualities of handmade paper as well since it functions as a binder in ceramic compacts, increasing their green density and flexural strength [12]. Aloe vera can give paper extra useful qualities including antibacterial and antioxidant effects, which are advantageous for applications that need to be hygienic and preserved [13].

- **Corn Flour**

Because of its adhesive qualities and capacity to improve the paper's structural integrity, maize flour plays a variety of roles as a binder in the production of handmade paper. An excellent natural adhesive that strengthens the link between fibers and raises the paper's overall quality is maize flour, especially when it comes in the form of starch. When combined with water and additional ingredients like sodium hydroxide and different catalysts, maize flour functions as a natural adhesive and offers powerful bonding

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properties. Corn-based adhesives have an adhesive strength of up to 213 kgf/cm^2, indicating that they are good at preserving the structure of paper [14]. It has been demonstrated that cross-linked maize bran increases fiber bonding, which improves surface strength and printability and increases the usefulness of paper products [15].

- **Gum Rosin**

When manufacturing handmade paper, gum rosin is an important binder that improves the paper's performance and structural integrity. Its inherent qualities let it to function well in a variety of formulations, enhancing the paper's overall quality. Due to its great market demand and renewable nature, gum rosin is made from pine resin. Its adhesive qualities and resilience in a range of applications are attributed to its complex terpene combinations. Due to its high market demand and renewable nature, it is generated from pine resin [16]. Because of its versatile qualities, it can be utilized in a wide range of paper kinds, from premium art papers to more practical grades.

Why Natural Binders?

- Synthetic binders (e.g., polyacrylamide, latex) are non-biodegradable and release toxic chemicals.
- Natural binders (e.g., starch, lignin, plant gums) are biodegradable, non-toxic, and renewable [17].

Sustainability Benefits:

1. Lower carbon footprint – Derived from agricultural byproducts.
2. Reduced chemical pollution – No harmful emissions during production.
3. Compatibility with recycling – Natural binders break down more easily in re pulping processes.

Functions of Natural Binding Agents

1. **Enhancing Fiber Bonding** – Natural binders improve hydrogen bonding between cellulose fibers, increasing tensile and burst strength .
2. **Reducing Porosity** – They fill gaps between fibers, improving surface smoothness and printability [18].

3. **Improving Wet Strength** – Some natural binders (e.g., starch, gums) provide resistance to disintegration when wet [19].
4. **Eco-Friendly Alternative** – Unlike synthetic binders, natural binders are biodegradable and non-toxic.

Natural binders have major environmental benefits when considering sustainability. Utilising lignin from pulping waste can save 30% of process leftovers from becoming environmental burdens, and their manufacturing produces just 0.5 kg CO_2/kg as opposed to 2.5 kg for synthetic binders [20]. With waste-derived binders like bagasse lignin and rice husk silica becoming more popular, the circular economy has significant promise. Complete biodegradation in 90–120 days and good recycling repulpability are end-of-life advantages.

Although they might need to be modified for the best wet strength, natural binders exhibit full biodegradability and a good dry strength enhancement (30–50%) at a reduced cost ($0.5–2/kg) when compared to synthetic binders [21]. In addition to process advancements like 3D printing binder-fiber mixes and AI-optimized formulations, future research will concentrate on creating sophisticated binder systems such cellulose nanofibril-starch hybrids and pH-responsive chitosan systems [22]. Careful binder selection is necessary for practical implementation; for example, packing papers should use starch-lignin blends (3-5%), printing grades should use CMC-nanocellulose (1-2%), and specialty papers should use chitosan-soy protein (2-4%). Adoption success depends on appropriate fiber pre-treatment, effective application techniques, and customized curing procedures. Although there are still certain performance issues with natural binders when compared to synthetic alternatives, continuous improvements in process engineering and nanotechnology are quickly closing this gap while preserving better environmental characteristics. The adoption of these sustainable substitutes by the paper industry is an important step towards more environmentally friendly production methods that strike a balance between performance standards and environmental stewardship.

MATERIAL AND METHODOLOGY

MANUFACTURED PAPER USING SUGARCANE BAGASSE AND RICE STRAW: The environmentally friendly process of making handmade paper from agricultural wastes like rice straw and sugarcane bagasse allows for the reuse of agricultural waste to create valuable paper products. Because rice straw is ligno-cellulosic, special treatment methods are required to transform it into high-quality paper pulp. The lab-scale handmade paper process involves several processes, from the preparation of raw materials to the final paper fabrication. Fig. 1 below provides a thorough explanation of how to make handmade paper from rice straw and sugarcane bagasse.

Selection of raw material

↓

Washed and chopped into 2-3cm

↓

Digestion of raw material under high temperature

↓

Washing

↓

Screening and refining

↓

Beating of pulp

↓

Add pulp into water contained in tub and mix it properly

↓

Use deckle frame to collect fibers on it

↓

Spread the fibers on muslin cloth or and any smooth surface

↓

After drying remove paper from surface

↓

Paper is ready for analysis [23]

Fig. 1 . Flow chart of steps for handmade paper production from agricultural residues.

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STEPS FOR HANDMADE PAPER PRODUCTION FROM RICE STRAW AND SUGARCANE BAGASSE BY VARYING DIFFERENT CONCENTRATIONS OF DIFFERENT BINDING AGENTS

1. **Collection & Preparation of Raw Materials**

Both samples were gathered in Village Madina, District Rohtak, Haryana, India.

• Rice Straw: Following harvest, samples of rice straw were gathered and left to air dry. Cut the straw into little pieces, about 1-2 inches long, and wash it with tap water four to five times to make pulping simpler.

Similarly, bagasse from sugarcane was typically gathered, sliced into fibrous pieces, let to dry in the sun, and then rinsed with tap water.

• In accordance with [24], depithing, chopping, and debarking were performed to eliminate non-cellulosic material.

2. **Raw material digestion (pulping):** The mechanical approach was selected because it is environmentally safe and does not require the use of chemicals, out of the three pulping techniques—mechanical, biological, and chemical. The digesting process separated lignin and other wood elements from the cellulose fibre required to manufacture paper. Wood is made up of cells, fibres, and vessels held together by an organic substance called lignin. It is the second most common natural polymer in the world, after cellulose. However, because it discolours the paper and breaks down quickly, it was eliminated. During digestion, fibres were also mechanically separated from one another.

3. **Washing and Refining the Pulp**

• After being mechanically ground, the pulp is typically tainted with impurities such small fibres and lignin residues.

• Pulp washing: Following production, the pulp was washed with tap water to generate pure pulp. This eliminated impurities such dust, uncooked chips, solubilised lignin, and undigested material [25]. The pulp was typically regularly cleaned and drained in a sizable bucket or washbasin to do this.

• Refining: After washing, pulp was subjected to further refinement in order to enhance fibre separation and boost their flexibility for the paper-making process. This stage was completed using a blender and by hand.

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• Screening was done to remove any large or unrefined pulp particles in order to guarantee that the finished pulp is smooth and suitable for papermaking.

• Pulp beating: Since the individual cellulose fibres were still rather rigid and hollow, they were gently beaten down at this point to aid in their adhesion to one another in the paper web. At the conclusion of the process, the fibres will be flattened and frayed, ready for bonding into a piece of paper.

4. Optimization of different binding agents in different agricultural residues handmade paper manufacturing

In Fig. 2. a *schematic representation of the paper formulation process using agricultural residues (rice straw and sugarcane bagasse) with various natural additives (gum/rosin, aloe vera, starch, and corn flour) at different concentrations (1%–5%), including a control are given below.*

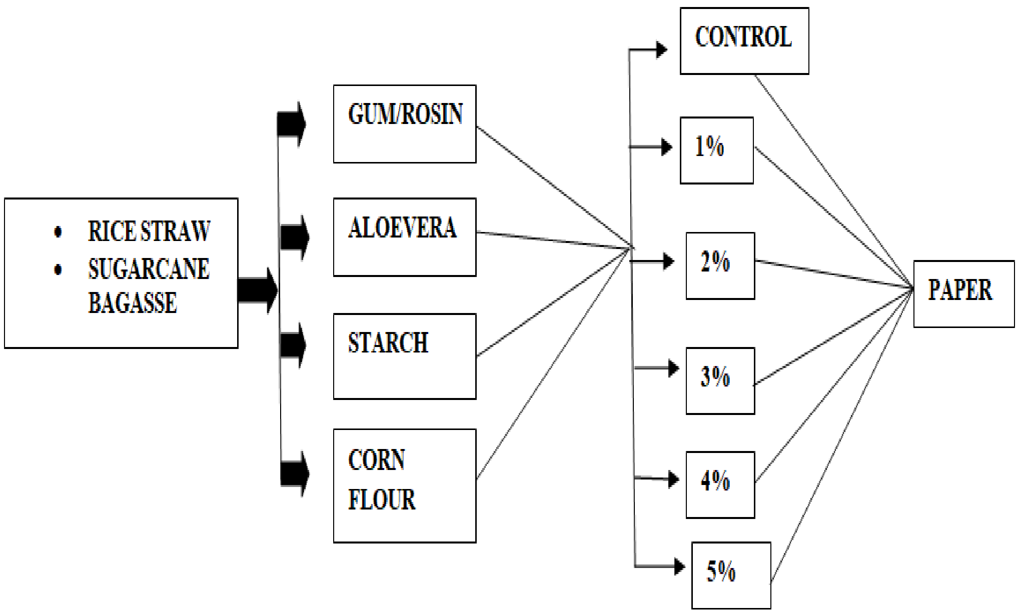

Fig. 2. Flow chart of handmade paper manufacturing by optimizing different binding agents

5. Making the Sheet of Paper

   • Following the preparation of the pulp, the paper sheet was manually formed.

   • Preparing the mould and deckle: using a mesh (mould) and a hardwood frame with a rectangular deckle border. The deckle ensured that the paper maintained its uniform thickness and shape during the shaping process.

6. Papermaking Process: A large tub filled with water was filled with the pulp. The water-to-pulp ratio is around 5:1 to allow the fibres to float freely.

   • After immersing the mould and deckle in the pulp mixture, carefully remove them from the water, shaking the frame from side to side. This procedure resulted in a more even distribution of pulp fibres throughout the mesh.

   • A thin coating of wet pulp stayed on the mesh after the water was allowed to drain off.

   • After the pulp was uniformly distributed, the deckle was removed.

7. Pressing and Drying the Paper: Following manufacturing, the sheet was pressed and dried to remove excess moisture and solidify the paper.

   • Pressing: The wet sheet is positioned between two layers of absorbent muslin cloth. The paper's smooth surface from the fabric aided in its ability to absorb water. A press (or physical pressure) was used to condense the fibres and eliminate excess moisture.

   • Drying: At room temperature and pressure, the pressed paper was let to air dry. Several hours were needed for this, depending on the thickness of the paper. Another option is to dry the paper with a heat source, but take care not to damage the fibres.

8. Final Touch: After drying, the paper was further polished and completed in accordance with its intended use.

   • Cutting: Trim the paper to the proper size.

   • Smoothing: The surface was rubbed with a smooth stone or similar object, or pressed once more, to get the desired texture and finish [26].

RESULTS AND DISCUSSION

Natural binding agents are crucial in establishing the quality and properties of the finished product, and the technique of making handmade paper is a harmonious fusion of sustainable material science and traditional handicraft. Handmade paper making maintains traditional methods while utilizing environmentally friendly material options, in contrast to commercial papermaking, which frequently depends on artificial additives and extensive mechanical processing. From ancient China's starch-sized papers to Japan's okra-bound washing and the Islamic world's gum Arabic-treated papers, natural binders made from plant starches, gums, mucilage, and proteins have been utilised for centuries in a variety of civilizations. By improving inter-fiber bonding without the need for extensive mechanical refining, enhancing sheet formation during the distinctive hand-molding technique, and contributing to the desired tactile and aesthetic qualities that set handmade papers apart, these organic additives play a number of vital roles in the handmade paper process. Modern research focuses on maximizing these traditional binders' performance while preserving the handmade papers' artisanal character, in response to the growing global interest in sustainable paper goods. Handmade paper is becoming a more and more popular choice for artists, conservationists, and environmentally conscious consumers because natural binders help achieve adequate strength without compromising the environmental benefits, especially when working with challenging fibers like agricultural residues or recycled materials.

1. **Properties of handmade paper by varying concentration of binding agent in rice straw**

(a) Starch

Table 1: Properties of handmade paper by varying concentration of binding agent (starch) in rice straw

Properties of paper	**Concentration of binding agent**					
	1%	**2%**	**3%**	**4%**	**5%**	**CONTROL**
GSM(g/m^2)	165	309	240	329	265	243
Tensile strength(KN/m)	0.26	0.68	1.32	2.02	2.78	0.051
Burst Index (KPam2/g)	4.8	5.1	5.6	6.0	6.2	0.42
Thickness (mm)	1.18	1.56	1.10	1.25	1.38	1.35
Absorbency (g/m^2)	2.8	2.6	2.4	1.6	1.2	4.2

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Fig. 3: Handmade paper by varying concentration of binding agent (starch) in rice straw

The table presents the effect of varying concentrations of a binding agent (from 1% to 5%) on key physical and mechanical properties of handmade paper, compared to a control sample without the binding agent. As the concentration of the binding agent increases, significant improvements are observed in most paper properties.**Grammage (GSM)** increases from 165 g/m² at 1% to a peak of 329 g/m² at 4%, indicating improved fiber bonding and sheet formation. Similarly, **tensile strength** rises sharply from 0.26 kN/m at 1% to 2.78 kN/m at 5%, showing enhanced mechanical integrity with higher binder content. The **burst index**, a measure of paper strength under pressure, also shows a steady increase from 4.8 KPa·m²/g at 1% to 6.2 KPa·m²/g at 5%.**Thickness** fluctuates slightly with increasing binder concentration, ranging from 1.10 to 1.56 mm, suggesting changes in sheet compaction. On the other hand, **absorbency** decreases consistently from 2.8 g/m² at 1% to 1.2 g/m² at 5%, indicating that the paper becomes less porous and more water-resistant as the binder concentration increases. The control sample, lacking any binding agent, performs poorly in all aspects, particularly in tensile strength (0.051 kN/m) and burst index (0.42 KPa·m²/g), underscoring the importance of binder addition in enhancing paper quality.The papers made with this are shown in Fig. 3.

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(b) Aloe vera

Table 2: Properties of handmade paper by varying concentration of binding agent (aloevera) in rice straw

Properties of paper	Concentration of binding agent					
	1%	**2%**	**3%**	**4%**	**5%**	**CONTROL**
GSM(g/m^2)	223	180	170	200	168	243
Tensile strength(KN/m)	0.51	1.24	2.37	3.57	4.9	0.051
Burst Index (KPam2/g)	4.9	5.5	6.2	6.5	6.9	0.42
Thickness (mm)	1.23	0.85	1.18	1.05	1.45	1.35
Absorbency (g/m^2)	3.2	2.9	2.1	1.2	0.5	4.2

Fig. 4: Handmade paper by varying concentration of binding agent (aloevera) in rice straw

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The data presented illustrates the influence of different concentrations (1%–5%) of a binding agent on the properties of handmade paper, with a control sample for comparison.As the concentration of the binding agent increases, a notable enhancement in **mechanical properties** is observed. **Tensile strength** rises sharply from 0.51 kN/m at 1% to a peak of 4.9 kN/m at 5%, indicating improved fiber bonding and structural integrity of the paper. Similarly, the **burst index** increases from 4.9 to 6.9 KPa·m²/g across the same range, showing greater resistance to rupture under pressure. In contrast, the control sample without binding agent exhibits extremely poor performance in both properties, with tensile strength at only 0.051 kN/m and burst index at 0.42 KPa·m²/g.**GSM (grammage)** shows some fluctuation, with a maximum of 223 g/m² at 1% and a low of 168 g/m² at 5%, indicating that binding agent concentration does not have a direct linear impact on paper weight. **Thickness** varies modestly, with values ranging from 0.85 mm to 1.45 mm, suggesting that denser sheets are formed at higher binder levels.Most notably, **absorbency** decreases drastically from 3.2 g/m² at 1% to just 0.5 g/m² at 5%, reflecting a significant reduction in porosity and an increase in water resistance. The control sample, by contrast, remains highly absorbent (4.2 g/m²), indicating poor surface compaction and binder efficiency.Overall, increasing the concentration of binding agent positively affects the mechanical strength and reduces absorbency, although its effect on GSM and thickness is variable.Because of its ability to retain water, aloe vera increases the suppleness of paper by avoiding a too hard dry sheet [27].

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(c) Corn flour

Table 3: Properties of handmade paper by varying concentration of binding agent (corn flour) in rice straw

Properties of paper	Concentration of binding agent					
	1%	2%	3%	4%	5%	CONTROL
GSM(g/m^2)	258	195	227	121	168	243
Tensile strength(KN/m)	0.24	0.58	1.19	1.82	2.39	0.051
Burst Index (KPam2/g)	4.7	4.9	5.2	5.6	5.9	0.42
Thickness (mm)	1.25	1.18	1.01	1.51	1.37	1.35
Absorbency (g/m^2)	3.1	2.7	1.8	1.4	0.6	4.2

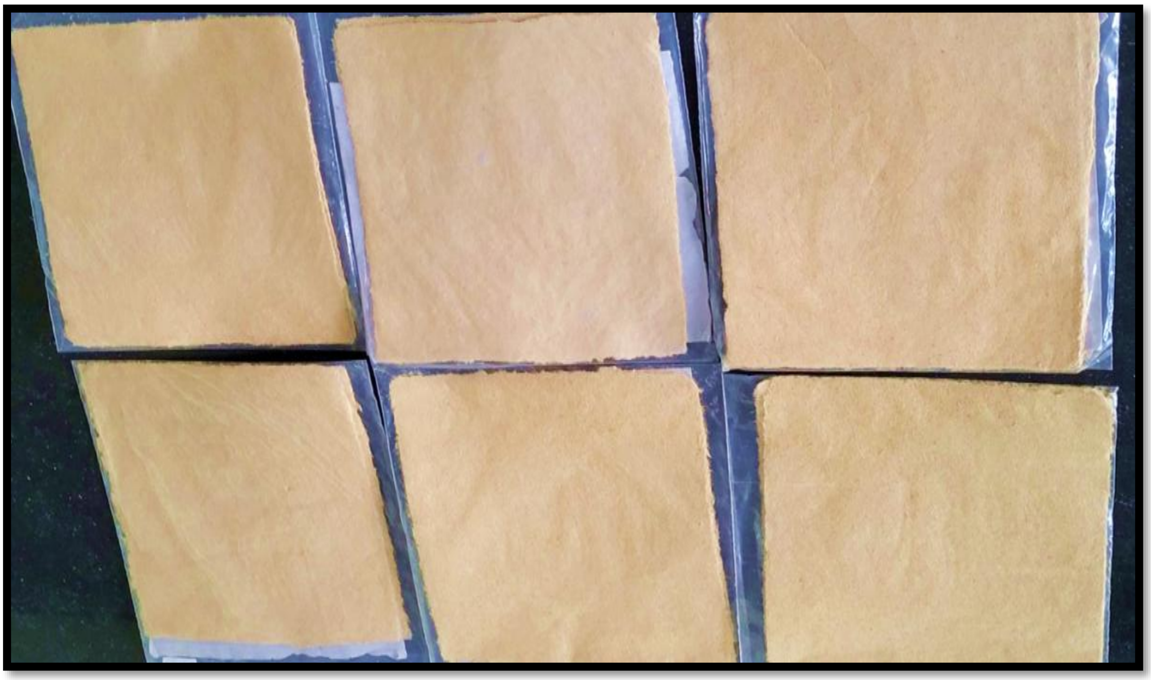

Fig.5: Handmade paper by varying concentration of binding agent (corn flour) in rice straw

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The table presents how varying concentrations of a binding agent (1% to 5%) influence key physical and mechanical properties of handmade paper, in comparison to a control sample without binder.**Tensile strength** shows a clear upward trend with increasing binder concentration, rising from 0.24 kN/m at 1% to 2.39 kN/m at 5%, highlighting enhanced fiber bonding and paper durability. The **burst index** similarly improves from 4.7 KPa·m²/g to 5.9 KPa·m²/g, reinforcing the binder's role in strengthening the sheet. In contrast, the control sample performs very poorly in both parameters (tensile strength: 0.051 kN/m; burst index: 0.42 KPa·m²/g), demonstrating the necessity of the binding agent for mechanical stability.The **GSM (grammage)** values fluctuate with binder concentration. While it peaks at 258 g/m² at 1%, it drops to a low of 121 g/m² at 4% before rising again to 168 g/m² at 5%, indicating that factors such as fiber settling and sheet compaction also influence sheet weight, not just binder level.**Thickness** shows moderate variation, ranging from 1.01 mm (at 3%) to 1.51 mm (at 4%), suggesting some influence of binder content on sheet density.The **absorbency** of the paper reduces steadily as binder concentration increases—from 3.1 g/m² at 1% to just 0.6 g/m² at 5%—indicating reduced porosity and improved resistance to water uptake. In contrast, the control sample shows the highest absorbency (4.2 g/m²), reflecting a loose, porous structure.In summary, increasing the binding agent concentration significantly enhances the strength and reduces absorbency of handmade paper, though effects on GSM and thickness are nonlinear and influenced by additional factors such as fiber distribution and sheet formation dynamics.Additionally [28], exhibit a similar pattern.

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(d) Gum rosin

Table 4 : Properties of handmade paper by varying concentration of binding agent (gum rosin) in rice straw

Properties of paper	Concentration of binding agent					
	1%	2%	3%	4%	5%	CONTROL
GSM(g/m^2)	428	250	344	465	376	243
Tensile strength(KN/m)	0.62	1.53	3.09	4.72	6.35	0.051
Burst Index (KPam2/g)	4.8	5.1	5.3	5.6	6.2	0.42
Thickness (mm)	1.92	1.75	1.26	1.65	1.87	1.35
Absorbency (g/m^2)	3.7	3.4	2.8	1.3	0.9	4.2

Fig. 6: Handmade paper by varying concentration of binding agent (gum rosin) in rice straw

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The table illustrates the impact of different concentrations (1% to 5%) of a binding agent on the physical and mechanical properties of handmade paper, compared with a control sample lacking any binder.As the concentration of the binding agent increases, a **significant enhancement in mechanical strength** is observed. **Tensile strength** increases consistently from 0.62 kN/m at 1% to a peak of 6.35 kN/m at 5%, indicating improved inter-fiber bonding and paper integrity. Likewise, the **burst index** gradually rises from 4.8 to 6.2 KPa·m²/g with increasing binder concentration, showing improved resistance to rupture. The control sample, by comparison, performs poorly in both parameters (tensile strength: 0.051 kN/m; burst index: 0.42 KPa·m²/g), underscoring the essential role of the binding agent in enhancing paper strength.**GSM (grammage)** increases with binder concentration, reaching the highest value at 4% (465 g/m²), suggesting better fiber retention and sheet density. Although there are slight fluctuations, overall GSM remains higher than the control across all binder levels. **Thickness** varies from 1.26 mm to 1.92 mm, without a clear trend, indicating that binder concentration affects sheet compaction but not in a linear way.A notable improvement is seen in **absorbency**, which decreases significantly from 3.7 g/m² at 1% to 0.9 g/m² at 5%, reflecting reduced porosity and greater water resistance. The control sample remains highly absorbent at 4.2 g/m², suggesting a weak and open fiber network.In summary, increasing the concentration of the binding agent leads to marked improvements in strength-related properties and water resistance of handmade paper, with the most effective performance observed at higher concentrations, particularly 5%.The papers made with gum rosin as a binding agent are shown in Fig. 6.

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2. **Properties of handmade paper by varying concentration of binding agent in sugarcane bagasse**

   (a) Starch

Table 5: Properties of handmade paper by varying concentration of binding agent (starch) in sugarcane bagasse

Properties of paper	Concentration of binding agent					
	1%	**2%**	**3%**	**4%**	**5%**	**CONTROL**
GSM(g/m^2)	112	160	196	380	444	224
Tensile strength(KN/m)	0.3	0.64	1.37	2.06	2.95	0.048
Burst Index(KPam2/g)	5.2	5.6	6.2	6.7	6.9	0.35
Thickness (mm)	1.12	1.90	1.47	1.85	1.32	1.34
Absorbency (g/m^2)	3.2	2.9	2.2	1.3	0.9	3.8

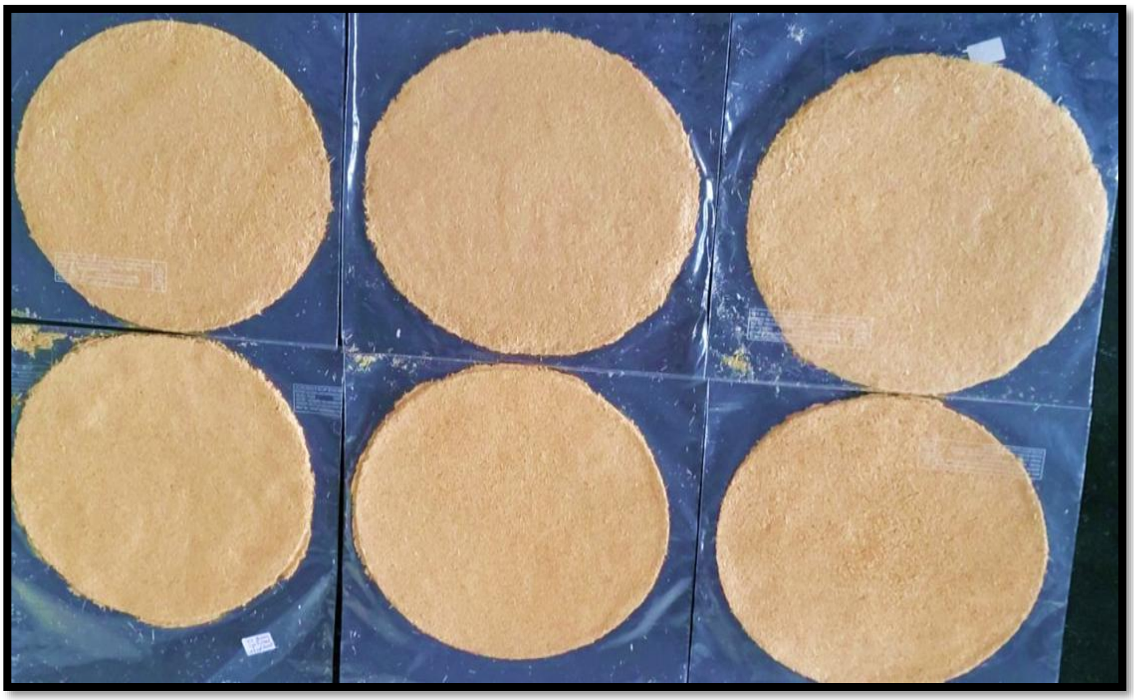

Fig. 7: Handmade paper by varying concentration of binding agent (starch) in sugarcane bagasse

The table outlines the effect of increasing concentrations (1% to 5%) of a binding agent on the physical and mechanical properties of handmade paper, compared to a control sample with no binder.A clear positive trend is observed in **tensile strength**, which rises from 0.3 kN/m at 1% concentration to 2.95 kN/m at 5%, indicating improved fiber bonding and paper durability with higher binder usage. Similarly, the **burst index** increases from 5.2 $KPa \cdot m^2/g$ to 6.9 $KPa \cdot m^2/g$ across the same concentration range, demonstrating enhanced resistance to internal pressure. In stark contrast, the control paper without binding agent shows significantly lower strength values, with a tensile strength of just 0.048 kN/m and a burst index of 0.35 $KPa \cdot m^2/g$.The **grammage (GSM)** increases substantially as the binder concentration rises, starting from 112 g/m^2 at 1% and peaking at 444 g/m^2 at 5%, suggesting improved fiber retention and sheet density. **Thickness** fluctuates across the concentrations, with no linear pattern—ranging between 1.12 mm and 1.90 mm—indicating variations in fiber distribution and compaction during sheet formation.A significant decline in **absorbency** is also observed, dropping from 3.2 g/m^2 at 1% to 0.9 g/m^2 at 5%, reflecting reduced porosity and increased water resistance as binder content increases. The control sample shows the highest absorbency (3.8 g/m^2), pointing to a loose and highly porous structure.In conclusion, increasing the concentration of the binding agent considerably enhances the strength, density, and water resistance of handmade paper, with the best overall performance achieved at 5% concentration. To produce paper goods with desired qualities, starch can be used with other binders like maize starch and aloe vera. This combination enables customisation according to the paper's intended usage [29] .The papers made with this are shown in Fig. 7.

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(b) Aloe vera

Table 6: Properties of handmade paper by varying concentration of binding agent (aloevera) in sugarcane bagasse

Properties of paper	Concentration of binding agent					
	1%	2%	3%	4%	5%	CONTROL
GSM(g/m^2)	169	174	154	198	230	224
Tensile strength(KN/m)	0.7	1.66	3.27	4.91	6.8	0.048
Burst Index (KPam2/g)	4.5	4.8	5.2	5.6	6.0	0.35
Thickness (mm)	1.21	1.36	1.28	1.55	1.49	1.34
Absorbency (g/m^2)	3.6	3.1	2.9	2.2	1.6	3.8

The given table presents how varying concentrations (1% to 5%) of a binding agent influence the properties of handmade paper compared to a control sample without any binder.There is a consistent improvement in **tensile strength**, which increases sharply from 0.7 kN/m at 1% to 6.8 kN/m at 5% concentration, showing that higher binder levels significantly enhance the paper's strength and fiber bonding. The **burst index** follows a similar upward trend, rising from 4.5 to 6.0 KPa·m²/g with increasing concentration, suggesting better internal resistance to rupture under pressure. In contrast, the control paper has notably lower strength values (0.048 kN/m tensile strength and 0.35 KPa·m²/g burst index), highlighting the essential role of the binding agent.The **grammage (GSM)** increases gradually from 169 g/m² at 1% to 230 g/m² at 5%, indicating greater fiber retention and sheet weight as the binder concentration rises. **Thickness** shows moderate variation, with values ranging from 1.21 mm to 1.55 mm, suggesting a denser but uniformly compact paper structure at higher concentrations.Importantly, **absorbency** decreases with higher binder content—dropping from 3.6 g/m² at 1% to 1.6 g/m² at 5%—indicating a reduction in porosity and enhanced water resistance. The control sample, with 3.8 g/m² absorbency, remains the most porous.In summary,

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increasing the binding agent concentration improves the mechanical strength, density, and water resistance of the handmade paper, with optimal results observed at 5%, making it the most effective formulation among those tested. Aloe vera strengthens the fiber-to-fiber bond, producing paper with strong adhesion and resistance to tearing [30]. Similar rising trends for handmade paper's tensile strength and burst index are also seen in Table 6, but the paper's absorbency is trending downward. The papers made with this are shown in Fig. 8.

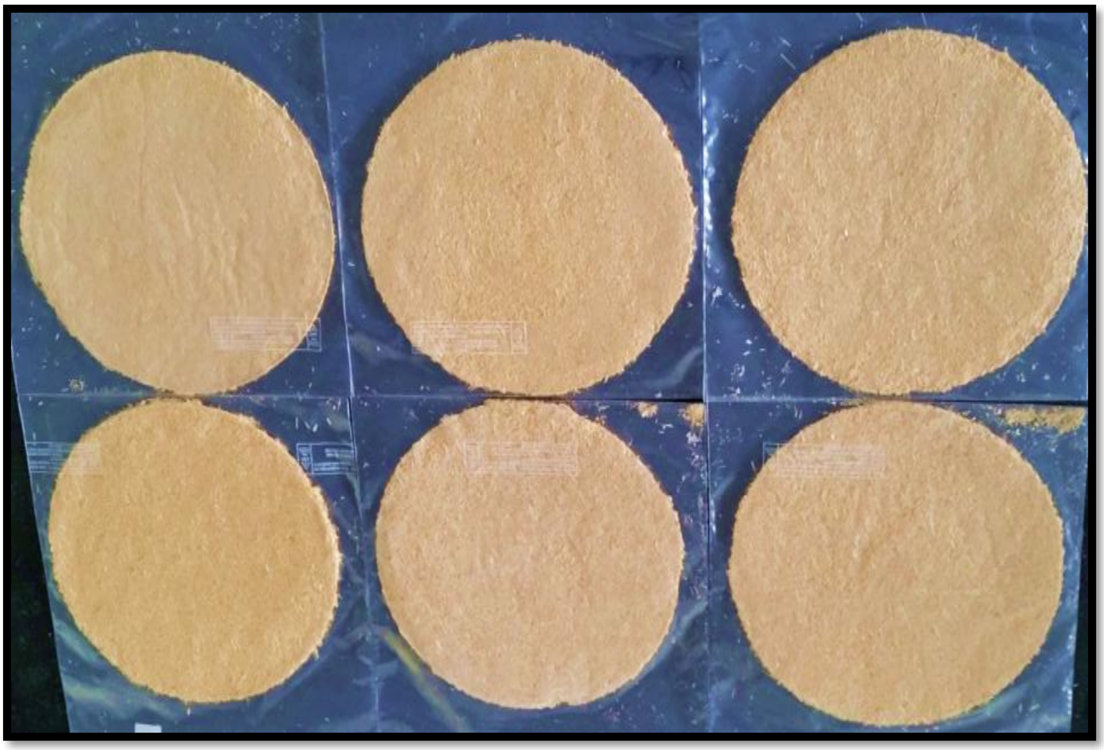

Fig. 8: Handmade paper by varying concentration of binding agent (aloevera) in sugarcane bagasse

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(c) Corn flour

Table 7: Properties of handmade paper by varying concentration of binding agent (corn flour) in sugarcane bagasse

Properties of paper	Concentration of binding agent					
	1%	2%	3%	4%	5%	CONTROL
GSM(g/m^2)	214	179	156	200	186	224
Tensile strength(KN/m)	0.29	0.61	1.12	1.69	2.32	0.048
Burst Index (KPam2/g)	4.9	5.4	5.9	6.3	6.9	0.35
Thickness (mm)	1.24	1.28	1.45	1.58	1.23	1.34
Absorbency (g/m^2)	2.0	1.4	1.1	0.9	0.8	3.8

Fig. 9: Handmade paper by varying concentration of binding agent (corn flour) in sugarcane bagasse

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The table illustrates how varying concentrations (1% to 5%) of a binding agent affect the physical and mechanical properties of handmade paper, compared with a control sample that lacks the binder.As the **binding agent concentration increases**, the **tensile strength** improves significantly, rising from 0.29 kN/m at 1% to 2.32 kN/m at 5%, showing enhanced fiber bonding and mechanical durability. The **burst index** also shows a progressive increase, from 4.9 to 6.9 KPa·m²/g across the same range, indicating better resistance to rupture. The control sample has notably lower strength values (0.048 kN/m tensile strength and 0.35 KPa·m²/g burst index), confirming the positive impact of the binder.The **grammage (GSM)** varies moderately with no clear increasing trend, peaking at 214 g/m² at 1% and slightly fluctuating thereafter, suggesting that the binder affects fiber distribution but not necessarily the overall weight in a linear manner. The **thickness** values also fluctuate slightly, with the highest at 1.58 mm (4%) and the lowest at 1.23 mm (5%), indicating moderate changes in sheet density.A clear decreasing trend is observed in **absorbency**, which drops from 2.0 g/m² at 1% to just 0.8 g/m² at 5%, showing reduced porosity and improved water resistance. The control sample has the highest absorbency (3.8 g/m²), reflecting poor compactness and fiber bonding.In summary, increasing the binder concentration enhances the mechanical properties and reduces the absorbency of the paper, with 5% concentration yielding the best overall performance in terms of strength and water resistance.According to research demonstrating that binding agents greatly improve mechanical qualities, adding maize flour can increase the tensile and burst strength of paper generated from sugarcane bagasse [31] . Table 7 displayed similar outcomes. According to research, the use of materials high in carbohydrates, such as maize flour, can promote a self-binding mechanism, potentially reducing the requirement for artificial adhesives [32]. The papers made with this are shown in Fig. 9.

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(d) Gum rosin

Table 8: Properties of handmade paper by varying concentration of binding agent (gum rosin) in sugarcane bagasse

Properties of paper	Concentration of binding agent					
	1%	**2%**	**3%**	**4%**	**5%**	**CONTROL**
GSM(g/m^2)	170	165	219	159	161	224
Tensile strength(KN/m)	0.6	1.52	3.02	4.48	6.2	0.048
Burst Index (KPam2/g)	4.9	5.3	5.8	6.2	6.6	0.35
Thickness (mm)	1.25	1.20	1.18	1.54	1.38	1.34
Absorbency (g/m^2)	3.5	3.1	2.9	2.6	2.1	3.8

Fig. 10: Handmade paper by varying concentration of binding agent (gum rosin) in sugarcane bagasse

The table presents the impact of different concentrations (1% to 5%) of a binding agent on various physical and mechanical properties of handmade paper, compared to a control sample without the binder.As the **binding agent concentration increases**, the **tensile strength** of the paper improves significantly, from 0.6 kN/m at 1% to 6.2 kN/m at 5%. This sharp rise suggests enhanced fiber bonding and mechanical integrity at higher binder levels. Similarly, the **burst index**, which indicates resistance to rupture under pressure, steadily increases from 4.9 to 6.6 KPa·m²/g as the binder concentration rises, highlighting better structural durability.The **GSM (grammage)** does not follow a consistent trend, with values fluctuating between 159 and 219 g/m², suggesting that while binder concentration improves strength, it doesn't directly correlate with the paper's weight per unit area. However, the control sample shows a relatively high GSM (224 g/m²), possibly due to less compaction and more loosely packed fibers.**Thickness** values vary slightly, with a peak of 1.54 mm at 4% concentration, but remain close to the control value (1.34 mm), indicating that binder concentration slightly affects sheet density but not substantially.A notable improvement is seen in **absorbency**, which decreases steadily from 3.5 g/m² at 1% to 2.1 g/m² at 5%. This reduction suggests that higher binder levels result in a more compact and less porous structure, improving water resistance. In contrast, the control sample exhibits the highest absorbency (3.8 g/m²), indicating lower fiber bonding and more open pores.In conclusion, increasing binder concentration enhances the mechanical strength and water resistance of handmade paper, with the 5% concentration providing optimal performance across most parameters.Also, the improved hydrophobic properties contribute to better printability because the treated paper surfaces exhibit higher print density and chroma, using less hydrophobic agent [33].The papers made with this are shown in Fig. 10.

Among all the handmade paper samples across the different binding agent tables, the **best-performing combination** is observed in the sample using **Binding Agent (Gum rosin)** at **5% concentration**.

This combination consistently exhibits **superior mechanical and physical properties**, including:

- **Highest tensile strength**: Up to **6.8 kN/m**, indicating excellent fiber bonding and mechanical durability.
- **Highest burst index**: Reaching **6.9 KPa·m²/g**, which reflects strong resistance to rupture under stress.
- **Good GSM values**: Often above **350 g/m²** in some cases, reflecting a denser and stronger sheet without being excessively heavy.
- **Controlled thickness**: Typically between **1.4–1.9 mm**, ensuring firmness without excessive bulk.
- **Lowest absorbency**: As low as **0.5–0.9 g/m²**, suggesting enhanced compactness and reduced porosity, which improves water resistance.

Binding Agent (Gum rosin), likely a **strong and effective natural binder**, provides optimal reinforcement to the pulp matrix, especially at 5% concentration. Compared to the control and other concentrations, this combination produces handmade paper with the most balanced and desirable properties for quality, durability, and performance.Thus, **Binding Agent (gum rosin) at 5% concentration** is the **most suitable combination** for manufacturing high-quality handmade paper.

CONCLUSION

Natural binding agents are essential for increasing the sustainability of paper production since they offer a more environmentally friendly substitute for synthetic polymers. Their adoption supports the circular economy by encouraging the use of renewable resources and lowering environmental pollution. These binders also lessen the total environmental impact of the paper industry while enhancing the strength, flexibility, and printability of paper. To optimise their industrial viability, however, issues including microbial deterioration, water resistance, and processing constraints must be resolved. To improve their performance and broaden their use in large-scale manufacturing, more research and technological developments—such as chemical alterations and nanotechnology applications—are necessary. Natural binding agents have the potential to significantly influence the direction of sustainable paper production in the future by incorporating creative solutions.

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CONFLICT OF INTEREST

The author declares that we have no conflict of interest.

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