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Production of Waste-Based Adhesive as an Educational Experience on Materials Sustainability

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Abstract

This work addresses an educational experience aimed at technical secondary schools specializing in materials science and technology, as well as relevant introductory university courses. The goal is, in particular, the self-production of adhesives from casein in different preparations taken from the restoration tradition to bond vegetable waste fibers, namely, obtained from sugarcane bagasse. The experience includes the production of different compositions of adhesives, the extraction of fibers from vegetable waste, the bonding process of fibers with the various adhesives, and the simple measurements and documentation carried out to compare the different configurations. This reflects an archetypal study on materials science, plus represents an application of its basic concepts to the development of natural materials as a way to accustom the students to the sustainable production, also carried out using historical recipes.

Keywords: Sugarcane bagasse; Casein; Starch; Educational experience; Sustainable materials; DIY materials

1. Introduction

The environmental crisis has forced a review of production and consumption cycles, pushing society towards the principles of the Circular Economy. This sustainable development paradigm, which aims to harmonize economic, environmental, and social aspects, requires not only the optimization of resource use but also a profound cultural shift. In this context, schools play a crucial role, and from an educational perspective, introducing the 7R principles (Reduce, Reuse, Respect, Reflect, Rethink, Recycle, and Redistribute) appears to be an effective means of developing informed and proactive citizens in a general approach to sustainability [1]. In line with this vision, the production of do-it-yourself (DIY) materials from what would otherwise be considered waste, or "secondary raw materials", appears to be a highly valuable pedagogical experience that

can be implemented within the school environment [2]. This not only allows children to familiarize themselves in a simple and practical way with the importance of material recovery, but also introduces them, in a tangible way, to the experimental method for developing new products [3].

Therefore, this work focuses on exploring the educational potential of creating eco-friendly adhesives (or bio-adhesives) derived from readily available natural raw materials. Specifically, the focus is on the preparation and characterization of casein-based adhesives, with and without the addition of lime, and adhesives made from corn starch and rice starch. These materials, although they are food products or by-products, at the end of their life represent a concrete alternative to traditional synthetic adhesives.

History documents a rich heritage of natural adhesives whose formulas, based on renewable resources such as proteins and carbohydrates, were fundamental in ancient civilizations for crafts, construction, and restoration. For example, casein-based adhesives, often mixed with lime to improve water resistance and durability, played a prominent role until the advent of modern chemistry, finding use in carpentry and restoration. At the same time, adhesives derived from corn starch and rice starch represent the prototypes of polysaccharide-based binders, known for their ease of preparation and biodegradability [4-7].

From this perspective, the rediscovery of these ancient glues in a school setting represents a powerful educational experience for developing a direct scientific approach through experimental procedures and the introduction of the principles of materials chemistry and physics, deepening understanding of the life cycle of materials and fostering critical awareness of environmental issues.

This article illustrates an educational path aimed at the preparation of ecological adhesives starting from casein, casein and lime, corn starch and rice starch. The feasibility, challenges, and pedagogical value of the procedures adopted will be discussed, offering a framework for implementing these experiments in schools, aiming to connect scientific knowledge with broader ecological awareness.

2. Method

2.1. Aims of the experience

One of the recent indications for the achievement of more sustainability in materials is the possible use of biomass waste, which is normally integrated in a fully bio-based material [8]. In particular, naturally derived adhesives represent a renewable and eco-friendly solution. Specifically, those based on casein and starch offer a significant advantage in terms of environmental sustainability thanks to their ease of production and the lack of harmful chemicals. At the same time, the use of water-based adhesives contributes significantly to the conservation of resources and energy, as well as ensuring environmental protection, as they exploit renewable energy sources and do not generate pollution [9-10].

2.2 The structure of the experience

2.2.1 Selected waste to be sustainably bonded

The main sources of plant fibers for the production of laminates to be bonded with self-developed adhesives can be derived from agricultural residues of plants grown for other purposes. For example, sugarcane has a typical structure depicted in Figure 1. After the crushing and pressing processes for sugar extraction, it leaves a fibrous residue called bagasse. In the biorefinery context, it is essential to convert these biological materials into lignocellulosic biomass for other products and/or materials [11].

Bagasse, as it is the case for most stem-like structures, includes the presence of secondary (liberian) fibrous

structure, mainly extending also to the epidermis with limited compositional variance according to the variety, more so on the ripeness and harvesting method [12] and depending on the variety, ripeness, harvesting method, and the milling method [13]. For the sake of the experiment, the fibers were extracted by hand.

Optical microscopy observations of the fibrous component of bagasse were performed using an Iscope Euromex system at two magnifications (5x and 10x) to examine the fibers' morphology (Figure 2). A clear cellular structure is visible, with high level of compactness, while the tendency to fibrillation is very limited.

2.2.2 Production of adhesives

Regarding adhesives, expired materials such as milk, corn starch, and rice starch were selected to test their potential cohesive power. The use of milk for casein extraction has been a practice known since 1897 with the production of bioplastic elements known as galalith, which was patented by Spitteler and Krische [14]. Less well known are the casein-based glues formerly used to restore wooden boards, in the form of glue paste, to restore cohesion or fill gaps created by wood-boring insects [15].

Starch-based glues were formerly used as additives for the creation of organic pigments, yet later played an important role in paper production as mechanical reinforcement [16]. Their introduction as an adhesive paste occurred in 1927 with the Italian production of “Coccoina” [17].

To extract the casein, two liters of expired whole milk were poured into a metal container and heated over a flame until the temperature reached approximately 50°C. Following this, 240 ml of vinegar (6% acetic acid) was added to precipitate and coagulate the casein protein micelles. Once precipitation had occurred, the mixture was removed from the heat, and the resulting casein was separated from the whey by filtration. One liter of milk yielded approximately 300 g of casein, a whitish, lumpy substance.

In the experiment with casein, three types of samples were produced:

- A portion of the casein was left pure (CA) with the addition of distilled water to reduce its viscosity (CA samples).
- An amount of 5 g of casein was added with 1 g of sodium bicarbonate ($NaHCO_3$) and approximately 3 ml of distilled water to reduce its deterioration, as per industrial practice (CB samples) [18]
- An amount of 3 g of casein was added to 14 g of lime and approximately 30 ml of distilled water, following the casein/lime ratio reported in restoration (CC samples) [19]

For the corn starch- and rice starch-based glues, a 1:3 ratio was used with distilled water, and the mixture was placed on a hotplate set to no more than 100°C to allow the particles to hydrate and form a smooth paste. During this phase, it is important to stir the solution frequently (starch glues were indicated as AM samples and rice glues as AR samples).

The glues were subsequently produced a second time, increasing the doses while maintaining the same proportions. These were cast into 50 × 50 × 10 mm molds to measure volume shrinkage after drying, which took around 3 days.



Figure 1: Sugarcane plant, section and waste after extraction.

Photo produced in: https://BioRender.com

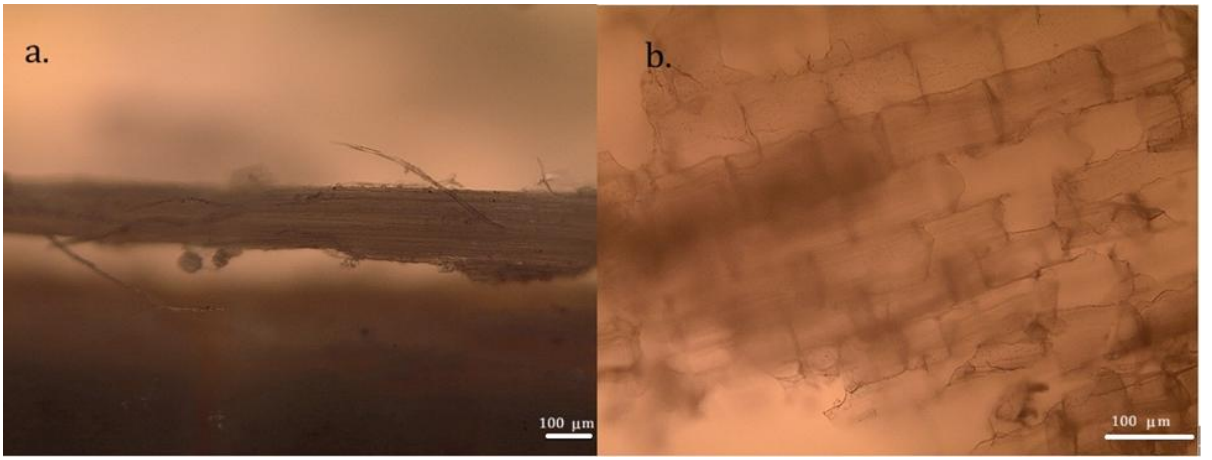


Figure 2: Morphology of bagasse fiber surface magnified at: (a) 5x, and (b) 10x



Figure 3: Example of adhesive production: a.) the resulting casein separated from the whey by filtration; b.) addition of sodium bicarbonate; c.) casein in 50 x 50 x 10 mm molds; d.) fiber gluing with casein.

2.2.3. Fiber bonding

The bagasse fibers were manually cut to a length of 50 mm for insertion into the mold. Before applying the glue layer, the fibers were arranged side by side in the mold, avoiding gaps despite their slight geometric irregularity, to cover the mold surface. The glue was then spread using a spatula, and another layer of fibers was placed on top. Two types of specimens were created: the first with the fibers of the two layers arranged parallel in a unidirectional layout, the second with the fiber layers oriented at 0° and 90° in a cross-ply layout (Figure 4).

3. Results and discussion

Shrunk casein-based adhesives after drying are represented in Figure 5; the lowest level of volume withdrawal is reported in the lime-casein blend (sample CC). Numerical data are reported in Table 1: it needs to be noticed that, though in the latter sample a significant weight reduction is still observed, the material tends to spread the shrinkage over the whole surface area, instead of concentrating on the edges, which should result in a more even and uniform bonding effect.

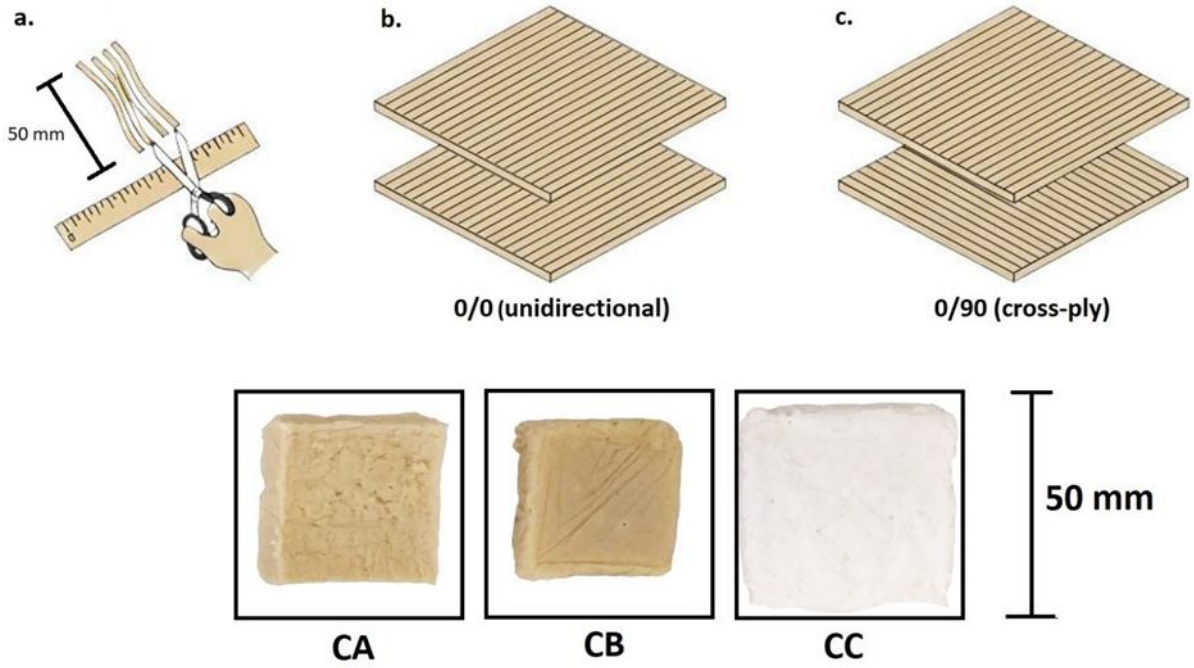


Figure 5: Dried casein-based adhesives and their withdrawal with respect to the dimension of the mold

Table 1: Weight reduction of casein-based adhesives after drying

Series	Initial weight (g)	Final weight (g)	Withdrawal (cm^3)	Withdrawal (wt.%)
CA	33.37	12.05	11,31	45.24
CB	34.30	8.50	16.90	67.60
CC	25.59	12.30	10.18	40.75

In Figure 6, the different laminates after drying are depicted. The unidirectional ones (A) produced with casein-based adhesives clearly showed some criticalities, less so for the sodium bicarbonate-loaded ones (CB): the situation is clearly improved for the corn starch and rice starch laminates. In contrast, much sounder structures are found in the cross-ply laminates (B), where fiber separation does not occur after drying, so that they can be supposed to possibly represent a bonding solution. However, side views indicate the large variability obtained in any case over the laminate thickness following the drying process (Figure 7). As with adhesives, the lowest weight reduction for laminates (Table 2) is obtained with the casein-lime blend, which can be proposed for further development as an adhesive.

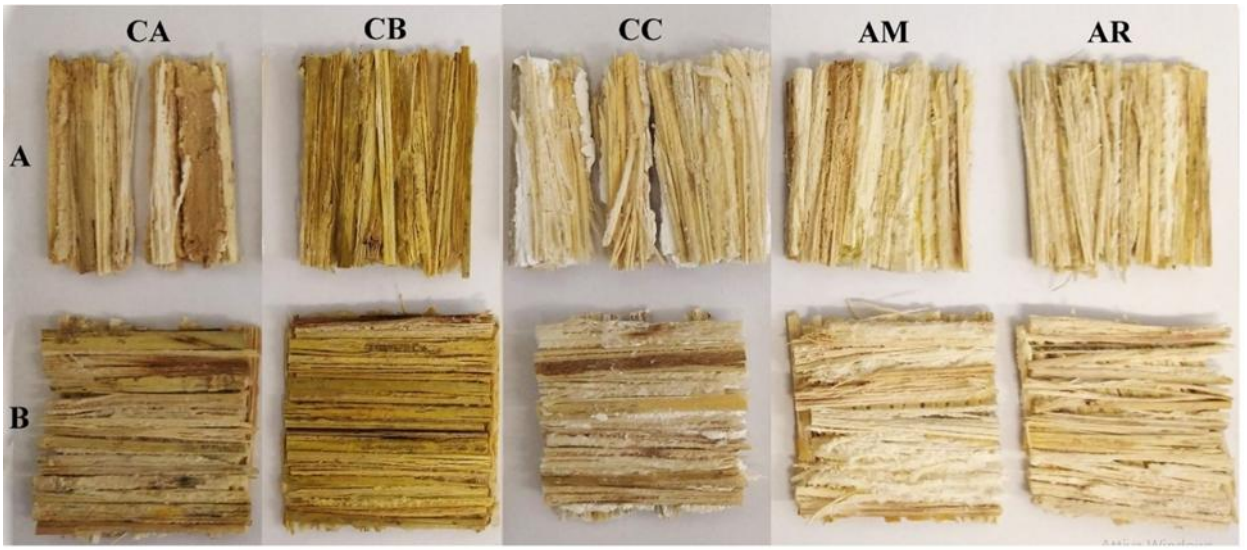


Figure 6: Top surface of the various categories of samples: a. Unidirectional: b. Cross-ply

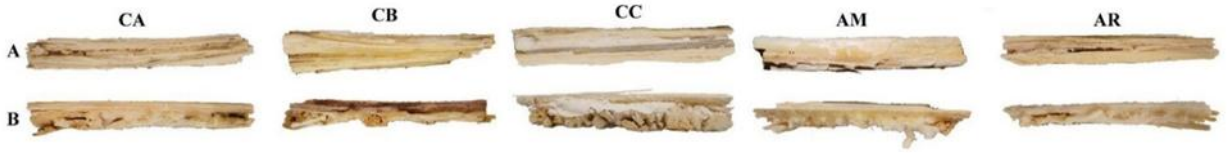


Figure 7: Side view of the various categories of samples: a. Unidirectional: b. Cross-ply

Table 2: Weight reduction of the various laminate samples

2. **Sample**	**3. Initial weight** 4. **(g)**	**5. Final weight** 6. **(g)**	**7. Weight reduction** 8. **(wt.%)**
9. CA1	10. 10.29	11. 4.04	12. 60.74
13. CA2	14. 10.29	15. 4.21	16. 59.09
17. CB1	18. 9.95	19. 3.93	20. 60.50
21. CB2	22. 10.90	23. 4.30	24. 60.55
25. CC1	26. 11.75	27. 6.39	28. 45.62
29. CC2	30. 10.28	31. 5.70	32. 44.55
33. AM1	34. 7.56	35. 3.15	36. 58.33
37. AM2	38. 7.21	39. 2.74	40. 62.00
41. AR1	42. 5.21	43. 2.73	44. 47.60
45. AR2	46. 6.20	47. 2.95	48. 52.42

The work presented above has been specifically developed as an exercise for students in technical schools to engage with sustainable materials and, more broadly, with materials science, as for example developed in [20] on banana fibers. Following this general statement, the information that can be obtained from the simple experiments carried out can be summarized below in some operational points, which can be further developed:

1. Documentation on different adhesive categories, namely casein [21], corn starch [22], and rice starch [23], highlighting their different role and potential on cellulose-based material.
2. Extraction of fibers from selected waste, namely bagasse, and the difficulties of the process of obtaining long and reasonably regular stretches [24]
3. Taking simple measurements about laminate morphology, also making use of optical microscopy, and the drying process resulting in the shrinkage of adhesive, which is an essential issue to control the production of bonded material, as recognized by recent investigations on in-situ characterization [25]

This concerns the introduction to a simple characterization process, to address in the selection and in the improvement of the material, of course, to be completely implemented with further considerations. In this specific case, an iterative process of material development needs to be carried out, consisting of gradual modifications to the recipe and the production process. This will be assisted by a series of specific measurements, in particular concerning adhesive shear testing [26], ageing process, which involves the integration of fungi inhibitor agents for the biological glue [27], and regularization of the geometry, possibly with surface and edge preparation, e.g., by paper sanding [28]. Other aspects would delve into a potential pre-industrialization process, such as the use of pressure to improve bonding.

4. Conclusions

A study involving the initial development of an educational experience for the self-development of an adhesive for fibers extracted from sugarcane bagasse. The adhesives will be based on casein, according to three different recipes, and compared with what is obtained with two types of starch-based adhesives. Two types of laminates were obtained, with a unidirectional and cross-ply orientation, respectively. The educational content about materials science, concerning data logging, observation, and reporting, so as to allow the comparison of the

different configurations, in view of further testing and developments.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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