From Waste to Worth: Fabrication and Analysis of Bioplastic Films Derived from Sugarcane Bagasse Cellulose Acetate

Yuvraj Nair

Navrachana International School; Vasna - Bhayli Main Rd, Bhayli, Vadodara, Gujarat

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Abstract- *This study aims to develop and characterize novel bioplastic films derived from cellulose acetate extracted from sugarcane bagasse, a readily available agricultural waste in India. Cellulose was extracted from sugarcane bagasse using hot water treatment, followed by delignification with sodium hydroxide. The extracted cellulose underwent activation and acetylation processes. Bioplastic films were then synthesized using varying ratios of cellulose acetate, chloroform, and glycerol. The resulting films were characterized for their physical, and biodegradation properties using techniques such as thickness measurement, density determination, moisture content and absorption tests, and biodegradability assays. The bioplastic films exhibited thicknesses ranging from 0.79 to 1.12 mm and densities between 0.87 and 0.97 g/cm^3. Moisture content and absorption increased with higher glycerol content. The films demonstrated improved biodegradability compared to conventional plastics, with the highest biodegradation rate of 9.3 × 10^{-5} g day^{-1} m^{-2}. This research contributes to the development of sustainable packaging materials and offers a potential solution for managing sugarcane waste in India. The produced bioplastics show promise for various applications, particularly in the packaging industry, and could help reduce environmental pollution caused by conventional plastics. This study fills a gap in existing literature by developing a novel bioplastic material from sugarcane bagasse and provides valuable insights into the properties and potential applications of cellulose acetate-based bioplastics.*

Keywords

Bioplastics, Sugarcane bagasse, Cellulose acetate, Sustainable packaging, India

1. Introduction

The global plastic crisis has prompted researchers and industries to seek sustainable alternatives to conventional fossil fuel-based plastics. Bioplastics, which are plastics derived from renewable biomass sources, have emerged as a promising solution to this environmental challenge. The concept of bioplastics has evolved significantly since their inception in the early 20th century, from early materials like celluloid to modern, sophisticated formulations that rival the properties of traditional plastics (1).

Bioplastics offer several advantages over their fossil fuel-based counterparts. They are derived from renewable resources, reducing dependency on finite petroleum reserves. Many bioplastics are biodegradable or compostable, helping to mitigate the environmental pollution caused by conventional plastics. Additionally, the production of bioplastics often results in lower greenhouse gas emissions, contributing to efforts to combat climate change (2).

In recent years, there has been a growing trend in utilizing agricultural and food waste to produce bioplastics. This approach not only addresses the issue of plastic pollution but also provides a solution for managing organic waste. Researchers worldwide have explored various waste materials for bioplastic production. For instance, Ogunmolasuyi et al. (3) developed bioplastics from yam peelings, while Bilal et al. (4) utilized banana peel waste. Other studies have focused on materials such as potato peels (5), corn husks (6), and even coffee grounds (7).

The development of bioplastics from agricultural waste offers a multifaceted solution to several global challenges. It addresses the pressing issue of plastic pollution, provides a sustainable waste management strategy for agricultural residues, and creates potential new revenue streams for farmers. Furthermore, as these materials are often biodegradable, they can contribute to reducing the accumulation of plastic waste in landfills and oceans (8).

For a country like India, with its large agricultural sector and growing environmental concerns, bioplastics derived from agricultural waste present a particularly attractive opportunity. India faces significant challenges in managing both plastic waste and agricultural residues. The development of bioplastics from locally available agricultural waste could simultaneously address these issues while promoting sustainable economic development in rural areas (9).

While numerous studies have explored bioplastics from various fruit and vegetable wastes, there is a pressing need for solutions that utilize waste materials commonly available in India. Sugarcane, being one of the most widely cultivated crops in India, generates substantial amounts of bagasse as a byproduct. This readily available waste material presents an excellent opportunity for bioplastic production (10).

Despite the potential of sugarcane bagasse as a feedstock for bioplastics, there is a gap in the existing literature regarding its use in developing high-performance, biodegradable materials. This research aims to fill this gap by developing a novel bioplastic based on cellulose acetate extracted from sugarcane bagasse. By utilizing this abundant agricultural waste, this study not only contributes to the field of sustainable materials but also offers a potential solution tailored to the Indian context.

This paper presents the development and characterization of bioplastic films derived from sugarcane bagasse-based cellulose acetate. We explore the effects of various plasticizers and their concentrations on the physical, mechanical, and biodegradation properties of the resulting bioplastics.

2. Literature Review

Bioplastics have emerged as a promising sustainable alternative to conventional petroleum-based plastics, which pose significant environmental challenges due to their non-biodegradability and accumulation in ecosystems (11). The global production of traditional plastics reached 360 million tons in 2019, with only 9% being recycled (12). In contrast, bioplastics are derived from renewable biomass sources and offer advantages in terms of biodegradability, reduced carbon footprint, and utilization of agricultural waste streams (11).

A key driver for bioplastics research has been the valorisation of food loss and waste (FLW) streams, which represent a significant environmental and economic challenge globally. It is estimated that approximately one-third of food produced for human consumption is lost or wasted annually, amounting to about 1.3 billion tons (11). Utilizing these FLW streams as feedstocks for bioplastics production presents an opportunity to reduce waste while creating value-added products.

Researchers have investigated a wide variety of fruits, vegetables, and agricultural residues as potential sources for bioplastics. Otoni et al. (11) provide an extensive review of FLW streams that have been explored, including apple pomace, banana peels, brewer's spent grains, coconut fibre, coffee husks, corn stover, grape pomace, mango wastes, citrus peels, pineapple leaves, potato peels, rice husks and straw, sugarcane bagasse, and wheat straw, among others. These diverse biomass sources contain valuable components such as cellulose, hemicellulose, pectin, lignin, and starch that can serve as building blocks for bioplastic materials.

Recent research has shown growing interest in using protein-rich agri-food by-products for bioplastics production. These materials are often used as animal feed, but their use in bioplastics can generate added value (13). Some protein sources that have been studied include soy protein isolate (SPI) from soybean oil production (14), pea protein isolate (PPI) derived from the selection of quality peas (15), crayfish and rice proteins (16,17), egg albumen (18), wheat gluten (19), fish scales (19), and cottonseed protein (20). Among these, SPI and PPI have shown particular promise. SPI bioplastics exhibit excellent superabsorbent characteristics, while PPI bioplastics demonstrate good antimicrobial activity (13).

Starch is another widely studied raw material for bioplastics due to its abundance, biodegradability, and annual renewability (21). Starch can be obtained from various sources such as cereals, grains, seeds, roots, tubers, and stems. Cassava starch, in particular, has been extensively investigated for biodegradable film production. Recent studies have explored the use of corn starch blended with polyvinyl alcohol (PVA) to produce bioplastic films with improved properties (22). These corn starch/PVA bioplastics have showed promising mechanical properties and biodegradability, with potential for applications in packaging and other industries.

Various processing methods have been explored for bioplastics production, including injection moulding, compression moulding, extrusion, and solvent casting. Injection moulding has been identified as a common and effective technique for producing bioplastics. Processing parameters such as mould temperature and post-injection time can significantly influence the properties of the resulting materials (13).

Despite the progress made in bioplastics research, several challenges remain. Achieving mechanical and barrier properties comparable to conventional plastics is still a significant hurdle. Many bio-based materials still exhibit inferior mechanical and barrier properties compared to conventional plastics (12).

Improving water resistance while maintaining biodegradability is another challenge. The hydrophilicity and water solubility of some bioplastics limit their applicability in certain environments (12).

Evaluating the environmental impacts of bioplastics production and use is crucial. While bioplastics offer potential environmental benefits, their production and end-of-life management must be carefully assessed to ensure a net positive impact.

3. Materials and Methods

3.1 Materials

Bagasse was obtained from a local sugar mill in Gandhara. Analytical grade chemicals including acetic acid (98%), sulfuric acid (98%), toluene (99.8%), acetic anhydride (98%), sodium hydroxide (98%), and hydrochloric acid (37%) were purchased from AsesChem. Chloroform (99%) and glycerol (99.5%) were obtained from Biomall. All chemicals were used without further purification.

3.2 Cellulose Extraction from Bagasse

200 grams of bagasse underwent hot water treatment at 80°C for 2 hours to extract cellulose. The extracted cellulose was then dried at 60°C for 24 hours in a convection. The dried cellulose was ground into a fine powder using a mortar and pestle and delignified with 1M sodium hydroxide solution at 80°C for 2 hours. The product was washed thoroughly with distilled water until neutral pH was achieved, dried at 60°C for 24 hours, ground, and sieved through a 200-µm mesh. The final yield of cellulose was 40.36 grams.

3.3 Cellulose Activation

Cellulose activation was carried out in a reflux setup. 10 grams of cellulose was mixed with 100 mL of acetic acid and 50 mL of 98% sulfuric acid. The mixture was heated to 60°C and maintained for 3 hours. After the reaction, the product was transferred to a beaker, washed with distilled water, and filtered using a Büchner funnel with Whatman No. 1 filter paper. The activated cellulose was then dried at 60°C in an oven until constant weight was achieved.

3.4 Cellulose Acetylation

The activated cellulose underwent acetylation in a reflux setup. 10 grams of activated cellulose was mixed with 50 mL of 98% sulfuric acid, 50 mL toluene, and 100 mL acetic anhydride. The mixture was heated to 60°C and maintained for 4 hours. Excess toluene was evaporated using a rotary evaporator (R-100, Labline Stock Centre) at 60°C for 2 hours. The product was washed with distilled water until neutral pH was achieved and dried at 60°C in an oven until constant mass was obtained. The final yield of cellulose acetate was 37.43 grams.

3.5 Substitution Degree Calculation

The degree of substitution (DS) of cellulose acetate was determined using the titration method described by Wu et al. (23). 0.5 grams of cellulose acetate was dissolved in 25 mL of 0.5 M NaOH solution and heated to 50°C for 30 minutes with constant stirring. The sample was then titrated with 0.02 M HCl using phenolphthalein as an indicator. The DS was calculated using the following equation:

$$DS = \frac{162 \times (N_{NaOH} \times V_{NaOH} - N_{HCl} \times V_{HCl})}{1000 \times W - (M_w - 1) \times (N_{NaOH} \times V_{NaOH} - N_{HCl} \times V_{HCl})}$$

Where,

N = molar value of substance

W = mass of cellulose

M_W = molecular mass of bound substituent at cellulose

3.6 Bioplastic Synthesis

Five grams of cellulose acetate were mixed with distilled water. Varying amounts of chloroform (98%) were added and stirred until a homogeneous pulp was formed. Glycerol was then added to achieve ratios of 1:1, 1:2, 2:1, 1:3, and 3:1 (cellulose acetate:glycerol). The pulp was spread onto a glass petri dish and compressed to a thin layer using another petri dish. The samples were dried at 60°C in a convection oven for 1 hour. The resulting bioplastic films were carefully peeled off and stored in a desiccator at room temperature (25°C) and 50% relative humidity for 24 hours before characterization.

4. Characterization of Bioplastics

4.1 Thickness Measurement

The thickness of the bioplastic films was measured using a digital Vernier caliper with an accuracy of 0.01 mm. Ten measurements were taken at different positions for each sample, and the average thickness was calculated. The method was adapted from ASTM International (24) with slight modifications.

4.2 Density Determination

Density was determined by cutting the bioplastics into 1 cm × 1 cm squares. The mass was measured using an analytical balance (precision 0.0001 g). The density was calculated using the equation developed by Moshood et al. (25):

Density = Mass / (Thickness × Area)

43 Moisture Content

Moisture content was determined following the method described by Moshood et al. (25). The initial mass of the bioplastic samples was measured using an analytical balance. Samples were then oven-dried at 80°C for 5 hours. The final mass was measured, and the moisture content was calculated using the following equation:

MC (%) = (Initial mass - Final mass) / Initial mass × 100

4.4 Moisture Absorption

Moisture absorption was tested using the method described by Moshood et al. (25). The oven-dried samples from the moisture content test were immersed in distilled water for 24 hours at room temperature (25°C). The samples were then gently blotted with filter paper to remove surface water and weighed. Moisture absorption was calculated using the formula:

MA (%) = (Final mass - Initial mass) / Final mass × 100

4.5 Biodegradability

Biodegradability was assessed using a soil burial degradation test. Fresh 1 cm × 1 cm bioplastic samples were weighed and buried in garden soil with known composition and moisture content. The samples were kept buried for 21 days, maintaining constant soil moisture. After the test period, samples were carefully removed, cleaned, dried, and weighed. The biodegradability rate was calculated using the following equation:

Biodegradability rate = (Initial mass - Final mass) / 21

5. Results and Discussion

5.1 Thickness

A plastic film's thickness is critical. It can assess toughness of the plastic because it is a physical-tensile property. The thickness of a bioplastic must be considered because it should be able to resist load-bearing pressure.

An evident pattern is examined in the collected data: the higher the glycerol concentration, the higher the thickness. From Fig. 1, the thickness of the bioplastic films ranged from 0.79 to 1.12 mm, with higher glycerol concentrations resulting in thicker films. This is primarily due to the unique properties of glycerol. As a dense and viscous fluid, glycerol hinders flow and spreading during film formation, resulting in thicker films. This characteristic of glycerol adds to the complexity of bioplastic formation. This trend is similar to that observed by Lim et al. (22) in their study of cassava starch-based bioplastics, where increased glycerol content led to thicker films.

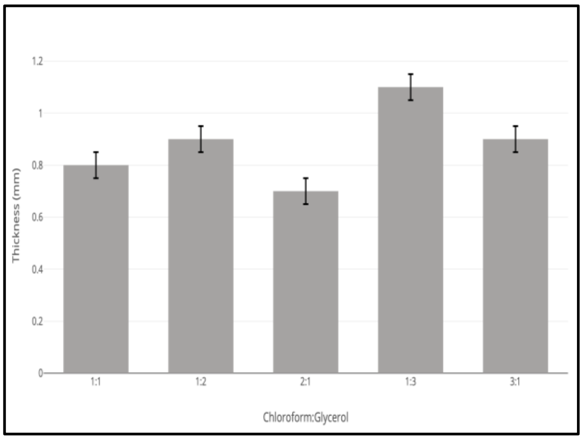

Figure 1: Thickness of bioplastic films with varying chloroform and glycerol ratios

5.2 Density

Density is a physical-tensile property. The higher the density, the lower a plastic film's elasticity. A clear pattern is seen in the results obtained: the higher the chloroform percentage, the higher the density. On a molecular level, chloroform has a higher mass (MR = 119.5 g/mole) than glycerol (MR = 92.09).

Fig. 2 shows that the values of density ranged from 0.87 g/cm^3 to 0.97 g/cm^3. These values are lower than those reported for starch-based bioplastics (1.2 - 1.3 g/cm^3) by Averous and Bouquillon (26) and comparable to the density range (0.87 - 1.20 g/cm^3) reported by Bežirhan Arikan and Bilgen (5) for potato starch-based bioplastics. The lower density of our cellulose-based bioplastics suggests potential advantages in applications where lightweight materials are preferred.

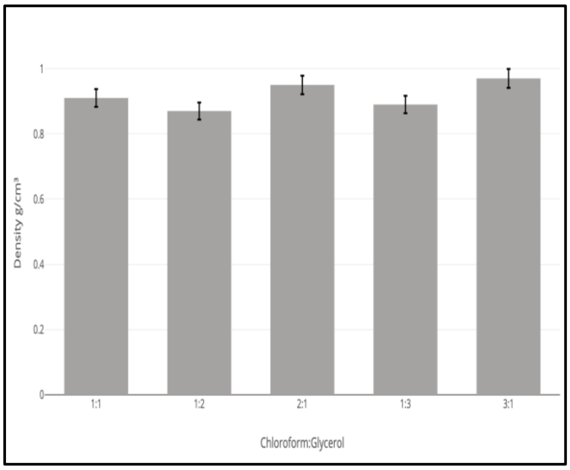

Figure 2: Density of bioplastic films with varying chloroform and glycerol ratios

5.3 Moisture Content

The moisture content of bioplastics refers to the percent mass of the bioplastic that was water after the production process was finished. The moisture content increased with the use of plasticizers. From Fig. 3, the bioplastic for which maximum glycerol was added for synthesis had the greatest moisture content (49%), and the bioplastic for which the highest percentage of chloroform was added had the lowest moisture content (30%). When the ratio between both was 1:1, the moisture content lay in the middle. A previous study in which banana peels were used to make starch-based biopolymers (4) has shown that glycerol-based bioplastics had a higher moisture content value. This is because glycerol is part of the hydroxyl group, which readily forms hydrogen bonds with water molecules and has a great affinity for them.

The moisture content of the bioplastics ranged from 30% to 49%, increasing with higher glycerol content. These values are higher than those reported by Averous and Boquillon (26) for starch-based bioplastics (15-25%), which can be attributed to the higher hydrophilicity of cellulose acetate compared to starch.

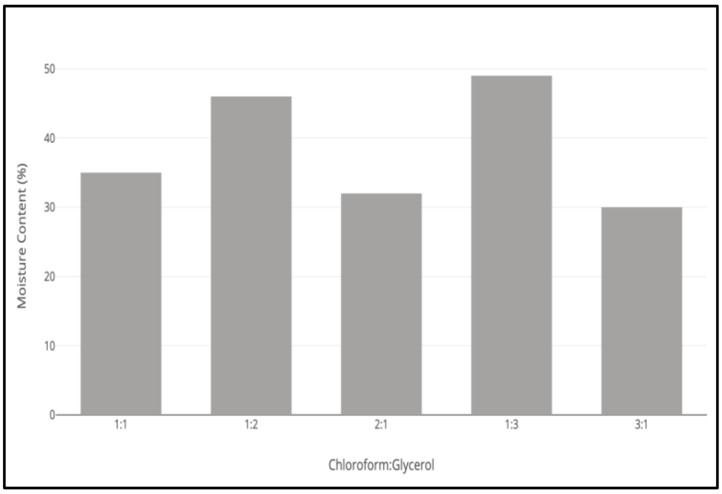

Figure 3: Moisture content of bioplastic films with varying chloroform and glycerol ratios

5.4 Moisture Absorption

One of the most common concerns about biodegradable plastics is their resistance and diffusivity with water, particularly for packaging purposes. In this study, the water absorption test was conducted over a span of 24 hours at room temperature (28°C). Through this, the stability of the plastic under humid conditions was measured. The moisture absorption of a plastic film is significant when considering its applicability in wet conditions. The immersion of the bioplastics in water caused water molecules to diffuse into the plastic's network chains and caused plastic swelling. At the initial stage, the absorption rate was speedy; however, this eventually slowed down and approached equilibrium as the number of vacant hydroxyl groups fell. As a plasticizer, glycerol increases a film's tendency to absorb water. This is due to the presence of a hydroxyl group and is consistent with previous research (4).

Moisture absorption values for this bioplastic ranged from 56% to 68%, with the lowest being when the glycerol percentage was a minimum and the highest being when the glycerol percentage was a maximum. This is lower than the values reported by Felix et al. (27) for rice bran-based bioplastics (85-200%). Cellulose acetate plastics tend to have higher moisture absorption ability than butyrate or propionate, and these plastics usually hold up more water molecules. This difference suggests that our cellulose acetate-based bioplastics may have better moisture resistance, potentially extending their shelf life in humid environments.

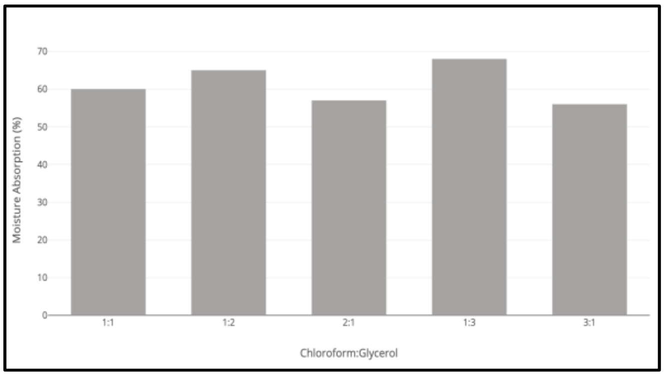

Figure 4: Moisture absorption of bioplastic films with varying chloroform and glycerol ratios

5.5 Biodegradability

The ability to biodegrade bioplastics is attributed to properties such as molecular weight, chemical structure, affinity to water, surface area, etc. (21). The affinity to water is a property that increases with the percentage of glycerol used for synthesis, and molecular weight is a property that decreases with the decrease in the rate of chloroform. Overall, the ratio with which the most biodegradable bioplastic was created is three parts glycerol to one part chloroform. The presence of the O-H group (hydroxyl) makes the bioplastic polar, and because of this, it can be broken down through hydrolysis with an acid or a base.

The highest biodegradability rate observed was 9.3×10^{-5} g day^{-1} m^{-2}, found in the bioplastic with the highest glycerol content. Although the film will require a long time to biodegrade, biodegradability is a step towards a brighter and safer future. The results from Fig. 5 indicate that the biodegradability of cellulose-based bioplastic films is far superior to starch-based bioplastic films (approximately 5.0 × 10^{-5} g day^{-1} m^{-2}) as found in existing literature (21). However, it is lower than the biodegradation rate reported by Ruggero et al. (28) for some commercial bioplastics (up to 2.0 × 10^{-4} g day^{-1} m^{-2}), indicating room for further improvement.

As the above results show, our cellulose acetate-based bioplastics show promising properties compared to many existing bioplastics, particularly in terms of biodegradability and moisture resistance. These results highlight the potential of bagasse-derived cellulose acetate as a sustainable material for bioplastic production.

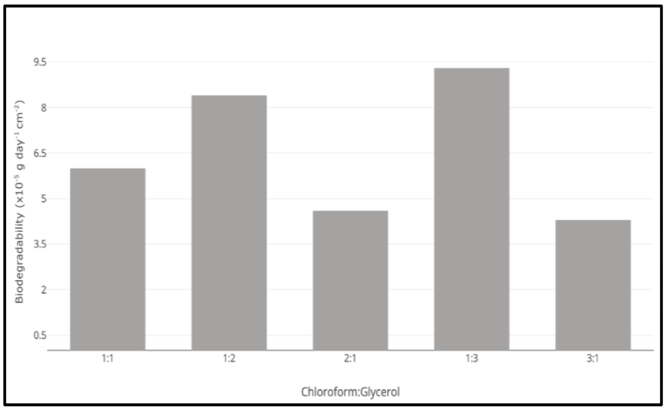

Figure 5: Biodegradability rates of bioplastic films with varying chloroform and glycerol ratios

6. Conclusion

This study successfully demonstrated the development and characterization of novel bioplastic films derived from cellulose acetate extracted from bagasse, a renewable agricultural waste product. Bioplastic films with varying properties were produced by manipulating the ratios of cellulose acetate, chloroform, and glycerol. The thickness of these films ranged from 0.79 to 1.12 mm, with densities between 0.87 and 0.97 g/cm^3, making them lighter than many conventional starch-based bioplastics.

The incorporation of glycerol as a plasticizer significantly influenced the moisture content and absorption properties of the bioplastics. Films with higher glycerol content showed increased moisture absorption (up to 68%), suggesting potential applications in controlled release systems or moisture-sensitive packaging. Biodegradability tests revealed that all synthesized bioplastics were biodegradable, with the highest biodegradation rate of 9.3 × 10^{-5} g day^{-1} m^{-2} observed in films with the highest glycerol content. This biodegradability rate is notably higher than those reported for many starch-based bioplastics, indicating a reduced environmental impact.

Despite the promising results, this study has some limitations. The laboratory-scale production may not fully represent the challenges of large-scale manufacturing processes. Additionally, the long-term stability and performance of these bioplastics under various environmental conditions were not extensively tested.

The implications of this research are far-reaching. By successfully developing biodegradable bioplastics from agricultural waste, this study contributes to the growing body of knowledge on sustainable materials. These bioplastics have the potential to significantly reduce plastic pollution and decrease dependence on fossil fuel-based plastics. Furthermore, the use of bagasse as a raw material could provide additional income streams for agricultural communities and promote the concept of a circular economy in the agricultural sector. Additionally, these cellulose acetate-based bioplastics from bagasse could lead to more sustainable and environmentally friendly packaging materials.

Future research could focus on optimizing the production process for large-scale manufacturing, investigating additional natural additives to further enhance properties, exploring potential applications in various industries, and conducting long-term degradation studies in different environmental conditions.

In conclusion, this study demonstrates the feasibility and potential of cellulose acetate-based bioplastics as a promising alternative to conventional plastics. The physical properties of these bioplastics, combined with their biodegradability and renewable source material, position them as strong candidates for future sustainable packaging solutions. As the world continues to grapple with environmental challenges, innovations like these provide hope for a more sustainable future.

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