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DEVELOPMENT OF BIOPLASTICS FROM TAWARO'S ENVIRONMENTALLY FRIENDLY SAGO STARCH (METROXYLON)

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Sustainable bioplastics made from Tawaro sago starch are investigated in the study. This study is motivated by the global need to lessen the environmental impact of petroleum-based polymers and discover greener alternatives. Tawaro sago starch's amylose concentration, moisture levels, and ecologically friendly qualities are examined in the study. It carefully blends sago starch, glycerol, and an acetic acid and water activator solution to create a bioplastic. The study will examine these bioplastics' chemical composition, crystalline structure, mechanical properties, and reactions to UV radiation and microbial development. Researchers and developers are interested in sago starch, a staple meal in Palopo City, South Sulawesi Province, Indonesia, as a sustainable material. Sago starch is advantageous due to its renewable nature and eco-friendly properties. XRD, mechanical characteristics, and microbiological development in sago bioplastic are examined in the study, providing valuable insights. Tawaro sago bioplastic has no heavy metals, according to XRD. The mechanical characteristics have improved significantly, reaching 2,867 N/mm^2. A 48-hour UV radiation exposure within limitations changed the chemical chain, causing the improvement. Furthermore, bacteria grow swiftly on sago bioplastic. This research promotes sago-based bioplastics as an eco-friendly alternative to traditional plastics, promoting environmental sustainability. This research supports the global drive to create eco-friendly materials. Using Tawaro sago starch, creative solutions for a greener, more sustainable future are possible, with bioplastics offering a compelling alternative to existing plastics and lowering their environmental impact

Keywords: X-ray diffraction, tawaro starch, ultraviolet radiation treatment, mechanical properties

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1. Introduction

Plastic packaging protects, preserves, and attracts customers [1]. Petrochemical-based plastics are becoming more prevalent, causing environmental issues. Petrochemical plastics are a social issue due to an ecological crisis [2]. Researchers are seeking renewable, sustainable alternatives to non-organic materials. Bioplastics are exciting alternatives to traditional polymers since they decompose quickly [1–3]. Biodegradable materials could solve plastic waste's environmental problems. The natural breakdown of these items meets packaging and product protection requirements, making them environmentally friendly. Innovation in non-petroleum materials improves sustainability [4]. Renewable materials are essential for lowering fossil fuel use and plastic production's environmental impact.

Conservation and environmental awareness have grown in recent years. Understanding this subject has changed our view of materials and their environmental impact. This global issue could be solved using biodegradable polymers instead of synthetic polymers in industrial applications and packaging [5]. Biodegradable polymers revolutionized material science and sustainability. Some polymers are made from biodegradable polysaccharides, complex carbohydrates, and proteins [6–9]. This distinguishes them from standard synthetic polymers, which can pollute for years. Renewable polysaccharides and proteins help reduce plastic waste's environmental impact. The promotion of sustainable behavior helps the circular economy. A closed-loop system of natural sources, function, and breakdown makes biodegradable polymers a sustainable solution. Developing and using biodegradable polymers demonstrates a dedication to reducing industrial and packaging waste.

Tawaro's sustainable sago starch could revolutionize bioplastic manufacture by improving biodegradability [10]. Starch's ability to form strong, flexible sheets makes it a promising bioplastic material. This alternative is chosen for its film-forming capabilities, cost-effectiveness, widespread availability, and renewable properties. These qualities make it a promising sustainable material development alternative. Biodegradable films contain lipids, proteins, fibers, and polysaccharides. Starch-based films have succeeded more than others. Potatoes, rice, corn, taro, and root tuber starches are used to make these films. These films show the many uses of starch as a bioplastic precursor. Starch makes up about 50 % of commercial biodegradable plastics [11].

Bioplastics constructed from different starches have been thoroughly investigated, revealing many sustainable material possibilities. Characterization investigations for jackfruit seed bioplastics are an example. These investigations examine the special features of glycerol-plasticized bioplastics [12]. Bioplastic composite production and characterization have advanced. A good example is starch and empty fruit bunches supplemented with epoxidized oils. According to [13], the text's combination was meticulously designed and outlined. As a reinforcing component in starch-based bioplastic films, Chitosan has received interest due to its potential to improve mechanical characteristics and performance. Chitosan-reinforced starch-based bioplastics have been extensively studied for their mechanical parts. This research has illuminated these materials' applicability and durability [14]. It is essential to acknowledge that the utilization of sago starch for bioplastic production remains an area with limited research conducted thus far. Additional research is required to investigate the progress and potential of utilizing sago starch as a raw material for producing environmentally friendly bioplastics. Therefore, research to develop ecologically friendly bioplastics based on sago starch is still relevant.

2. Literature review and problem statement

Bioplastics have come to the forefront in recent years due to their promise to reduce the adverse environmental effects caused by traditional plastics made from petroleum. These renewable resource-based substitutes provide a greener alternative to conventional plastics manufacturing. The Tawaro sago palm (Metroxylon sp.) yields a starch that shows promise as a raw material for bioplastics. Traditional cuisines in Indonesia frequently use sago starch, which may be abundant in places like Palopo City in South Sulawesi Province [15]. However, its use in bioplastics can increase the resource's value while reducing plastic waste. Numerous important characteristics and properties of sago-based bioplastics have been investigated. The bioplastic features are affected by several factors, such as the amylose content, the moisture content, and the contaminants in sago starch.

The study in [2] emphasizes developing sustainable natural bioplastics. This strategic approach emphasizes the need to lessen our dependence on finite fossil fuels and address the environmental impacts of traditional plastics. The study addresses plastic pollution by studying biodegradable bioplastics. This family of materials has the advantage of spontaneously degrading, leaving small ecological footprints. Thus, biodegradable bioplastics may help fragile ecosystems from plastic trash. The study examines bioplastics' ability to meet food packaging's strict functional requirements. This multidimensional challenge requires good performance and durability. The study emphasizes bioplastics' potential to improve food safety and longevity by preserving food. Despite this hope, the study highlights careful verification. Researchers must determine if bioplastics can compete with conventional polymers in various dimensions. Shelf life, barrier properties, and structural robustness are essential. These studies will ensure that bioplastic-packaged food is safe and well-preserved from manufacture to consumption.

The review in [4] thoroughly evaluates the bioplastic and mix recycling studies. It objectively evaluates the strengths and weaknesses of this crucial sustainable materials research topic to provide a balanced perspective. The review goes beyond bioplastics to examine a wider range of materials. Bioplastics, their mixtures, and biocomposites are included. The assessment acknowledges the recycling landscape's complexity and its many difficulties and potential by evaluating this variety of materials. The text emphasizes the practical importance of understanding recycled bioplastics' real-world ramifications and prospective applications. However, one must examine how these materials interact with recycling processes to understand this topic. A more extensive investigation of how bioplastic blends and biocomposites affect recycling operations and recycled material quality and efficiency will greatly improve our understanding. Detailed examples of successful submissions will further enhance the review. These case studies could show how recycled bioplastics have been integrated into various sectors and prove their practicality. Furthermore, detailed market research should examine recycled bioplastics' current and future potential in numerous sectors. This research should evaluate market demand, pricing dynamics, and competition to inform industry stakeholders and policymakers. While emphasizing bioplastic recycling's economic viability, a cost-benefit analysis of different recycling methods is helpful. This could help find and promote the most cost-effective recycling techniques.

The review in [7] explores starch-based bioplastics with fiber and nanoparticles. Its main goal is to study these increased bioplastics' properties and biodegradability. This broad analysis examines starch-based bioplastics' mechanical, thermal, and barrier properties. This holistic approach recognizes the complexity of these materials and that their practical applications frequently depend on a careful balance of their properties. Notably, the review addresses biodegradation performance. Given the increased emphasis on sustainability and environmental responsibility, starch-based bioplastics' biodegradability is crucial. The review's attention to this essential aspect shows a holistic approach to assessing these products. Several factors could improve the review's impact and accessibility. First, knowing the audience can help customize material. Tailoring the review to researchers, policymakers, and industry experts' requirements and viewpoints may improve its relevance and usefulness. Quantitative data and comparative analysis across research projects can also improve comprehension and usability. Using such data, users can draw conclusions and make informed judgments on starch-based bioplastics. Testing conditions affect biodegradation efficacy, so consider these. Addressing these variables and exploring biodegradation evaluation methodologies in the review would help readers grasp the subject better.

The study [9] analyzes how glycerol and clay nanoparticles affect biodegradable films made from cassava starch. This research goal emphasizes a dedication to eco-friendly packaging materials. The careful selection of materials and components makes this research stand out. The systematic use of glycerol as a plasticizer and clay nanoparticles as a reinforcing agent shows a comprehensive strategy for studying biodegradable films. This purposeful choice enables extensive film property study and sets a precedent for sustainable materials with improved qualities. This study evaluates mechanical properties, particularly tensile strength and elongation at break. These characteristics largely determine the film's mechanical performance. Understanding these films' stress and strain behavior is crucial, especially for packaging, where durability and flexibility are crucial. A complete approach is needed for informative and replicable research. Everything from clay nanoparticle preparation to film casting should be covered. Documenting outcomes helps researchers reproduce them and uncover and fix inconsistencies. Statistical analysis improves study rigor. These evaluations estimate the relevance of tensile property differences between formulations. Statistical validation gives research objectivity and credibility.

In the extensive study [16], waste fatty acids are converted into marketable bioplastics and smoothly integrated into a dark-fermentative hydrogen production process. A multifaceted study addresses two major environmental issues: fatty acid waste management and sustainable bioplastics. One of the most remarkable parts of this work is its creative usage of Bacillus tequilensis for specific applications. This choice involves a targeted use of waste fatty acids for bioplastic synthesis. To understand why Bacillus tequilensis was chosen over other microbial strains, the study must explain why. Which traits or talents make this strain ideal for the job? This selection's rationale and future study directions could be illuminated by such insights. Besides bioplastic synthesis, the study emphasizes dark-fermentative hydrogen generation from a holistic and resource-efficient approach. The integrated method maximizes waste material utility and minimizes environmental effects. The study could provide real-world examples of bioplastics and dark-fermentative hydrogen generation's uses and benefits to make the findings more realistic and applicable. Displaying how these new techniques might be used in diverse sectors or applications may increase acceptance and influence.

The study [17] aims to evaluate the effects of bentonite on yam extensively starch-based biodegradable bioplastic films. This study's target is clear and serves a specific need-improving yam-starch-based biodegradable films for food packaging. One of this study's highlights is its purposeful use of yam starch for bioplastic synthesis. Yam starch, a renewable natural resource, shows a dedication to sustainability in materials selection. This choice supports the global push to use sustainable bioplastic materials and reduce environmental impact. The study's approach goes beyond bentonite inclusion. It examines bioplastic sheets' mechanical and barrier properties. This comprehensive study understands that bioplastic film performance in practical applications depends on a complex balancing of various properties. Contextualizing the study within the sustainability landscape would improve its effect and utility. The study can emphasize its importance by relating it to global environmental and food packaging concerns. Additionally, it would be insightful to study yam starch's particular properties and discuss why it was chosen as the major material.

Despite the promising prospects of sago-based bioplastics, there is a need for a comprehensive characterization of these materials to optimize their production and application. Existing research has focused on specific aspects, such as chemical composition, crystalline structure, and mechanical properties, but a holistic understanding is lacking. Researchers are studying polar polymers, including polysaccharides and proteins, as biodegradable plastic alternatives to synthetic polymers. The development of degradable polymers is a significant step forward and environmentally favorable. Because they are renewable, these polymers may be used efficiently [18]. Tawaro sago starch, from Palopo, is a polysaccharide [15]. However, polysaccharide-based bioplastics have temperature resistance and material elongation issues [19, 20]. Further study is needed to address these constraints.

Thus, this study follows the SNI standard [21], which requires X-ray diffraction (XRD) to detect heavy metals in polar polymers before and after their conversion into biodegradable plastic sheets for packaging products. The study will also test bioplastics for UV resistance using ASTM D5208 UV radiation exposure. ASTM D822 material elongation testing is also planned. The project also seeks to test polymer materials' fungus resistance by assessing antibacterial characteristics using ASTM G21.

3. The aim and objectives of the study

The aim of the study is to identification the feasibility of utilizing sago starch (Metroxylon sp) from the Tawaro variety, sourced from Palopo City in South Sulawesi Province, Indonesia, as a primary material for environmentally friendly bioplastics.

To achieve this aim, the following objectives are accomplished:

– to identify the heavy metal content in sago starch and after processing it into bioplastic sheets using the X-ray Diffraction (XRD) method;

– to determine the mechanical properties of sago starch after its transformation into bioplastic sheets;

– to observe the proliferation of microorganisms on the surface of sago bioplastic specimens.

4. Materials and methods of experiment

4. 1. Object and hypothesis of the study

The object of the study is properties and characteristics of bioplastics made from Tawaro sago starch. This research aims to investigate these bioplastics' structural, mechanical, and environmental characteristics, specifically in relation to their potential use in environmentally friendly packaging. The study thoroughly examines the mechanical properties displayed by bioplastics made from sago. The analysis involves evaluating the subject's tensile strength, elongation at break, and modulus of elasticity under various conditions. The focus is examining how these mechanical attributes may change in response to external factors, specifically exposure to ultraviolet (UV) light.

The utilization of Tawaro sago starch in the production of bioplastics results in materials with advantageous structural, mechanical, and environmental characteristics. These properties render them well-suited for use in eco-friendly packaging applications. The bioplastics are anticipated to exhibit structural stability, improved mechanical strength, resistance to UV degradation, reduced vulnerability to microbial growth, and a biodegradable nature. As a result, they meet the requirements for sustainable packaging materials. The hypothesis proposes that Tawaro sago starch-based bioplastics could fulfill the demanding criteria of environmentally conscious packaging in today's world while providing beneficial characteristics in multiple aspects. The study seeks to evaluate and confirm this hypothesis by thoroughly analyzing these bioplastics.

The research assumes that bioplastics made from Tawaro sago starch demonstrate biodegradability and eco-friendliness. This foundational premise drives the exploration of their potential as environmentally sustainable materials for packaging. Moreover, it suggests that the structural integrity of bioplastics made from Tawaro sago starch remains intact even when subjected to external factors such as UV radiation. The foundational assumption is crucial for studying the mechanical characteristics and resistance to UV-induced degradation. In addition, the study is based on the premise that Tawaro sago starch is easily obtainable and can be used as a sustainable and renewable resource for the production of bioplastics. This assumption is crucial when assessing this resource's practicality and potential for growth.

The research may have been conducted in controlled environmental conditions to isolate specific factors, thereby reducing the influence of external elements on the properties of bioplastics. This approach facilitates a clearer understanding of the inherent characteristics of the materials. The study likely chose standardized testing conditions and procedures to make the characterization process more efficient. Although the simplification ensures consistency and facilitates result comparison, it may not fully reflect real-life scenarios. The investigation likely focused on short intervals of UV radiation exposure and microbial growth to expedite data collection. The simplification may fail to account for long-term degradation or the wider range of environmental impacts.

4. 2. Material

The Tawaro variety of sago trees, which are scientifically referred to as Metroxylon sp and can be found in the picture-perfect location of Palopo City, South Sulawesi Province, Indonesia, provided the source of the sago starch that was used in this pioneering research attempt. This starch served as the primary structural component. This specific sago starch was an excellent contender for creating bioplastic since it had an amazing amylose content of 36.49 % and a moisture level that was flawlessly dry at 0.0 %. The concept of precise hand layup was the methodology that was utilized in the process of producing these extraordinary specimens. A specific combination of materials was needed for this purpose. Eight grams of Tawaro sago starch, three milliliters of glycerol, and forty-six milliliters of an activator solution were expertly mixed. This activating solution was painstakingly prepared by carefully combining 2 % volume/weight acetic acid (CH_3COOH) with distilled water. The formulation was ingenious.

Fig. 1 illustrates the step-by-step process of bioplastic production, beginning with the primary raw material of sago and concluding with a series of thorough tests to evaluate the bioplastic's quality and performance. The first step of this complex process involves the production of the bioplastic material. The primary ingredients in this formulation are sago starch, acetic acid, glycerol, and pure water. The deliberate combination of these elements demonstrates a meticulous approach, establishing the groundwork for the following phases. The mentioned phase highlights the intentional adoption of sustainable and environmentally friendly materials in the production of bioplastics. This aligns with the principles of responsible and green manufacturing.

After the formulation stage, the bioplastic is subjected to a critical drying process. The utilization of an oven is a dependable technique for eliminating moisture, which guarantees that the bioplastic achieves the intended texture and strength. The drying phase plays a critical role in the production process, as it is crucial for successfully preparing the bioplastic material for further use and testing. After the completion of the oven process, the bioplastic is ready for a series of quality assessments. The tests are essential for assessing the bioplastic's performance and characteristics. The evaluation of the elastic modulus is one of the mentioned assessments. It offers insights into the material's elasticity and flexibility. XRD analysis is a technique that examines the crystalline structure of the bioplastic, providing insights into its molecular arrangement and properties. Moreover, the process of microbial growth testing involves a thorough examination of the bioplastic surface to identify any possible interactions with microorganisms. This aspect holds significant importance, particularly in applications such as food packaging.

The enchantment took place at a temperature of 70 degrees Celsius under strict control, where these components were continuously mixed with diligence until they reached a harmonic and consistent consistency. This impeccable combination of sago starch, glycerol, and the activator solution was the basis for a sago bioplastic specimen that would significantly contribute to the field. It was necessary to use a glass mold with an exact thickness of 0.6 millimeters to give this homogenous slurry a form that could be touched. The potential of an eco-friendly bioplastic was captured in this mold, which acted as a crucible for invention. After being meticulously positioned inside this mold, the material underwent a transformation process by being dried out for one hour at a temperature of one hundred and ten degrees Celsius. This crucial stage of the manufacturing process resulted in the construction the extraordinary sago bioplastic specimen, which paved the path for a sustainable and environmentally conscientious future.

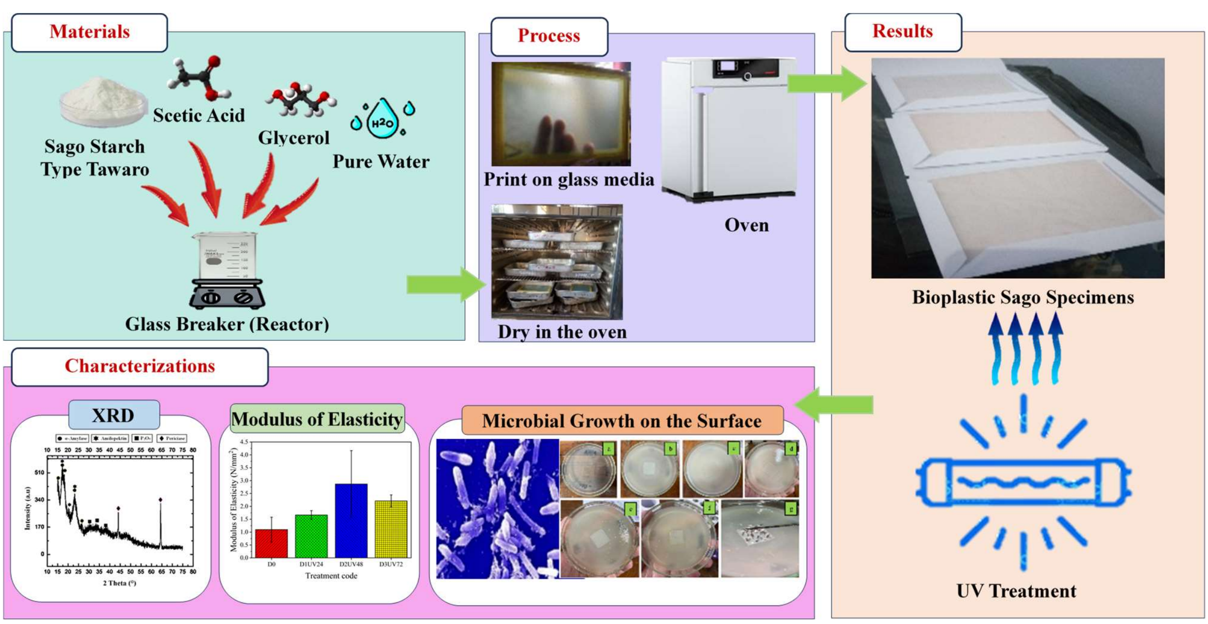


Fig. 1. The process of making and testing sago bioplastic material

4. 3. Methods and sample testing

The application of the X-ray Diffraction (XRD) technology in our research played an essential part in the characterization and identification of heavy metal content within the sago starch, both before and after the transformative process into bioplastic sheets. This was the case both before and after the bioplastic sheets were formed. Because of our analytical method, it is possible to investigate the structural features of the material in great detail, which assisted in accurately determining its composition and purity.

After this, our inquiry assessed the bioplastic material's resilience to the potentially damaging effects of UV radiation exposure under the stringent requirements outlined in ASTM D5208. This standardized testing showed that our bioplastic sheets exceeded the criteria for durability, confirming that they are suitable for various applications in which they might be exposed to sunlight and other environmental stressors.

To assess the material's mechanical qualities, particularly its elongation capability, let's resort to the well-respected standards established by the ASTM D822 committee. As a result of these experiments, it is possible to quantify how well our sago bioplastic could endure stretching and deformation, which provided with vital insights into its flexibility and potential utility in practical applications.

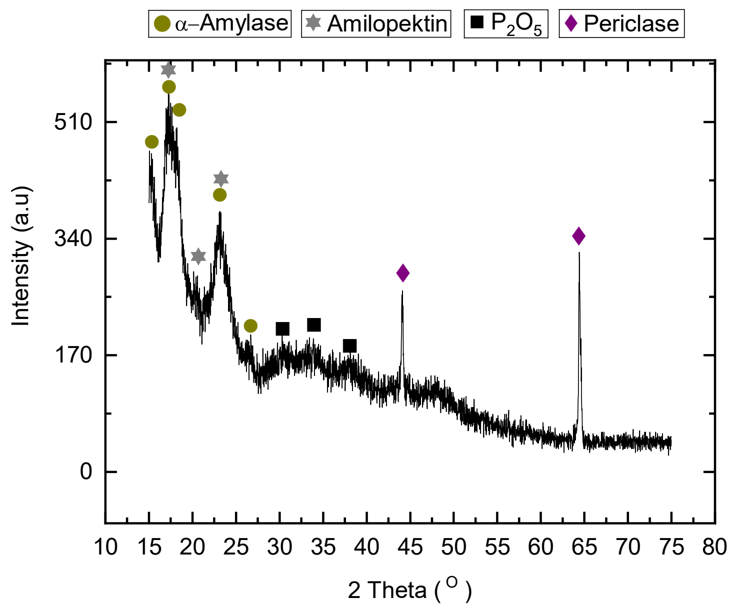
To determine the bioplastic material's level of microbiological resilience, let's subject it to a series of tests that adhered to the standards set forth by the ASTM G21. These tests simulated the presence of pathogenic bacteria and fungi. This aspect of our research highlighted the significance of the material's physical characteristics and its capacity to preserve its integrity in the face of microbiological challenges. As a result, the material is an all-around and versatile solution that can be utilized in various contexts.

In a nutshell, the path taken in our research has been defined by a dedication to conducting exhaustive tests and adhering to standards that are considered standard in the industry. It has received valuable insights into the heavy metal content, UV resistance, mechanical characteristics, and microbiological resistance of sago bioplastic through utilizing the XRD method, ASTM D5208, ASTM D822, and ASTM G21 standards. This multifaceted strategy guarantees that our bioplastic products meet and surpass the requirements for quality, performance, and sustainability.

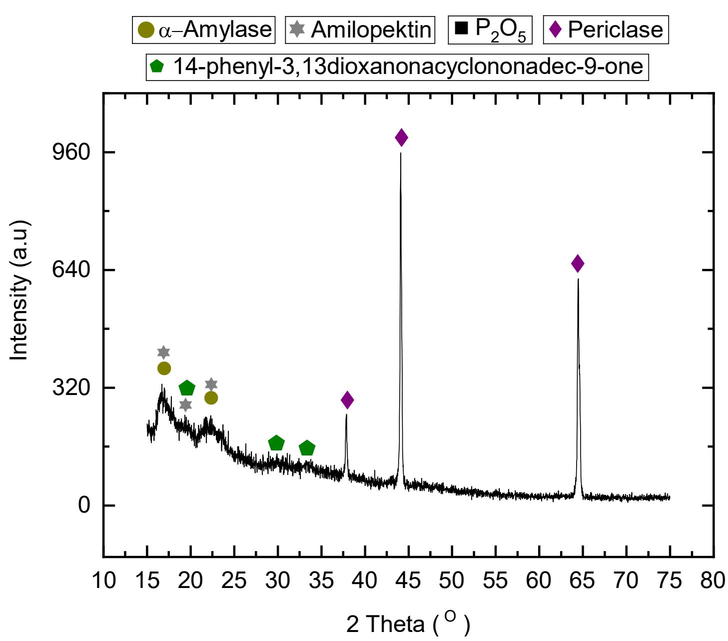
5. Results of the experiment using Tawaro environmentally friendly sago starch as a sago bioplastic

5. 1. Results of X-ray diffraction (XRD) of sago starch and sago bioplastic

The X-ray diffraction (XRD) analysis provided valuable insights into the structural composition of both Tawaro starch samples and the subsequent Bioplastic specimens. This analysis revealed various phases that were produced throughout the transformation process. Fig. 2, *a* depicts the diffractogram of the Tawaro starch sample, wherein several peaks are observed, each corresponding to distinct crystalline phases. The presence of the α-amylose phase was seen, as evidenced by different peaks at 2θ angles of 15.32°, 17.08°, 17.84°, 22.92°, and 25.19°. The observed phase displayed clearly defined crystal planes identified as (020), (013), (121), (123), and (024). The compound possessed the chemical formula ($C_6H_8O_4$) and displayed an orthorhombic crystal structure, which closely matched the information obtained from The International Centre for Diffraction Data (ICDD) database entry #00-043-1858. The discovery mentioned above highlights the high purity and structural stability level exhibited by the α-amylose phase in Tawaro starch.



a



b

Fig. 2. Diffractogram of: *a* — Tawaro starch; *b* — bioplastic specimens

The Amylopectin phase, which exhibited peaks at 2θ angles of 15.32°, 19.56°, and 22.92°, was distinguished by its chemical formula ($C_6H_{10}O_5$), which closely matched the data obtained from the ICDD database entry #00-052-2248. This phase is considered notable. This particular phase plays a crucial role in the overall structure of starch, hence making significant contributions to its distinctive characteristics. Nevertheless, impurity phases were identified inside the Tawaro starch samples amidst the clearly characterized phases. The identification of these impurities was conducted with great attention to detail, and they were determined to be P_2O_5 and Periclase (Mg_2O_4) based on data obtained from the Crystallography Open Database (COD) entries #96-231-1014 and #96-901-3251, respectively. The existence of these contaminants has prompted thought-provoking inquiries regarding their source.

The analysis of data from the ICDD#00-043-1858 and ICDD#00-052-2248 databases, as presented in Fig. 2, *b*, has provided valuable insights into the structural properties of the Tawaro starch and bioplastic samples, enhancing our understanding of these materials. The databases played a crucial role in helping to identify and verify the crystalline phases present in our samples. Upon further investigation, it is worth noting that, in addition to the primary α-amylose and Amylopectin phases, there were noticeable impurity phases originating from Tawaro starch. The presence of impurities, specifically P_2O_5 and Periclase (Mg_2O_4), was easily identifiable. This observation aligns with the information obtained from the COD database entries #96-231-1014 and #96-901-3251, confirming these impurities' presence. The discovery highlighted the intricate relationship between environmental factors and the makeup of Tawaro starch, prompting the need for additional research on the causes and effects of these contaminants.

The discovery of the 14-phenyl-3, 13-dioxanonacyclo nonadec-9-1 ($C_{92}H_{80}O_{12}$) phase, observed at angles of 2θ 30.58° and 33.94°, is highly fascinating. The presence of this distinct phase was discovered to align with the data obtained from the COD entry #96-402-6080. The unique aspect of this discovery lies in its origin, as it emerged from the interactions between glycerol, acetic acid, and sago starch. The finding highlights the ever-changing nature of the bioplastic synthesis process. The combination of glycerol, acetic acid, and sago starch created a fascinating phase, which presents opportunities for further investigation into the underlying mechanisms that drive its formation. Comprehending these interactions is crucial for customizing the production process to optimize the characteristics and effectiveness of sago-based bioplastic materials for particular uses.

The presence of contaminants in Tawaro starch is hypothesized to originate from groundwater or the sago tree's pith. During the extraction process, it is plausible that these contaminants may be assimilated by the sago starch, ultimately becoming included in the makeup of the substance. The discovery presented in this study provides opportunities for additional research on the origins and consequences of these contaminants since they could potentially impact the characteristics and uses of bioplastic materials derived from sago. The X-ray diffraction (XRD) analysis provided valuable insights into the crystalline phases in the Tawaro starch and bioplastic samples. Additionally, it suggested a complex relationship between environmental conditions and material composition, emphasizing the need for additional investigation in this intriguing study area.

5. 2. Results of mechanical properties of sago bioplastic

During our study, an extensive selection of bioplastic samples was carefully fabricated and afterwards exposed to a range of Ultraviolet (UV) radiation treatments to evaluate their durability and efficacy across different environmental circumstances. Table 1 shows the code for the bioplastic samples used in this study based on exposure to ultraviolet radiation. To conduct a comprehensive assessment of the mechanical properties of the bioplastic specimens, let's utilize the Universal Testing Machine - Lloyd L10K Plus. This particular instrument is widely recognized for its exceptional precision and reliability in accurately measuring material properties. The utilization of this apparatus facilitated the execution of elongation experiments on individual specimens, yielding significant observations regarding their inherent flexibility, stretchability, and general mechanical soundness.

Table 1

Bioplastic sample code

No.	Treatment code	Code meaning
1	D0	Lacking any ultraviolet radiation
2	D1UV24	Exposed to 24 hours of ultraviolet radiation
3	D2UV48	Subjected to 48 hours of ultraviolet exposure
4	D3UV72	Enduring an intensive 72 hours of ultraviolet Irradiation

The analysis of the elastic modulus, as shown in Fig. 3, offers valuable insight into the material's rigidity and reaction to UV exposure. The purpose of this parameter is to analyze the relationship between the stiffness of the bioplastic sago sample and the duration of UV exposure. The consistent exposure to UV light leads to a noticeable increase in the elastic modulus, suggesting that the material undergoes a stiffening effect when exposed to UV radiation. The user's text suggests a correlation between UV exposure and changes in the mechanical properties of bioplastics. These changes may result in increased rigidity and reduced susceptibility to deformation.

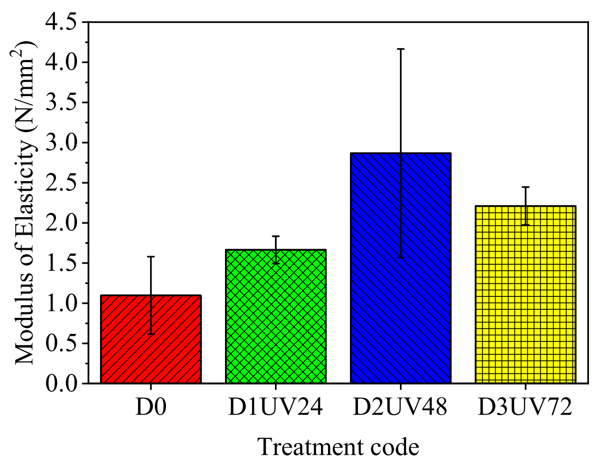


Fig. 3. Testing the modulus of elasticity on bioplastic before and after being treated with ultraviolet radiation

The study observed an impressive elastic modulus of 2.867 N/mm^2, the highest recorded. This high modulus was achieved after subjecting the material to 48 hours of UV light exposure. The significant increase in stiffness observed may be explained by the cumulative effects of UV-induced alterations in the material's structure, which enhance its mechanical integrity. In contrast, the samples not exposed to UV light demonstrated the lowest elastic modulus, measuring only 1.097 N/mm^2. The lower modulus suggests that the material is more flexible and pliable when in its original state, without exposure to UV radiation. The findings provide insights into the possible uses of sago-based bioplastics in situations that require stiffness and rigidity. The deliberate adjustment of UV exposure has the potential to customize the mechanical properties of a material to fulfill particular needs. In specific applications where maintaining structural integrity is crucial, extended exposure to UV radiation may be utilized to improve stiffness. Conversely, in other applications where flexibility is a priority, it may be preferable to limit UV exposure.

5. 3. Results of microbial growth on the surface of sago bioplastic

Monitoring sago bioplastic material surface microbial development is essential for product safety, stability, and quality. Testing helps meet regulatory requirements and guides product development. Testing microbial growth on bioplastics is careful and systematic to give reliable and valuable results. Controlled microbe application to the bioplastic product commences. This stage simulates real-world microbial infection, making it crucial.

The microorganisms are applied, and the testing process precisely controls environmental conditions to track their growth over time. Test results are trustworthy and reproducible in a controlled environment. Temperature, humidity, and light exposure are carefully controlled to imitate product lifetime conditions. The microbiological monitoring data is invaluable. They show the product's microbial growth prevention efficiency. This information is crucial for determining the product's hygienic and structural integrity under different settings.

Assessing bacterial proliferation on bioplastics entailed a systematic and rigorous examination protocol to evaluate the material's vulnerability to microbial colonization. The research investigation examined Bacillus subtilis bacteria, yielding significant findings on the interaction between microorganisms and the bioplastic material. The experimental procedure was initiated by introducing Bacillus subtilis bacteria onto Muller Hinton Agar (MHA) media, a commonly used bacterial cultivation and proliferation medium. The precise attachment of small bioplastic samples, with dimensions of 1.5×2 cm, was carried out on the agar media surface, as depicted in Fig. 4, *a*. The experimental arrangement emulated a situation where the bioplastic material might encounter possible microbial pollutants.

The incubation phase was initiated during the subsequent 24-hour period, facilitating the interaction between the bacteria and the bioplastic surface. The following observations done on the next day confirmed the presence of bacterial proliferation on the bioplastic sheet. The observed effect was consistent over three iterations of the experiment, indicating the material's inclination to facilitate bacterial colonization. The salient feature of this finding was the homogeneous distribution of bacterial proliferation across the entirety of the bioplastic sheet, which closely resembled the arrangement of bacterial colonies expanding in the immediate region of the plate, as illustrated in Fig. 4, *b*. The bacterial colonies exhibited a comparable hue on both the bioplastic and the surrounding plate, suggesting a strong resemblance in microbial activity. This finding underscores the susceptibility of the material to bacterial colonization. During the investigation, as the observation period extended to 48 hours, it was observed that there was a significant increase in bacterial growth on the surface of the bioplastic sheet, as depicted in Fig. 4, *c*. The observed phenomenon of the bacterial colonies exhibiting a progressive increase in

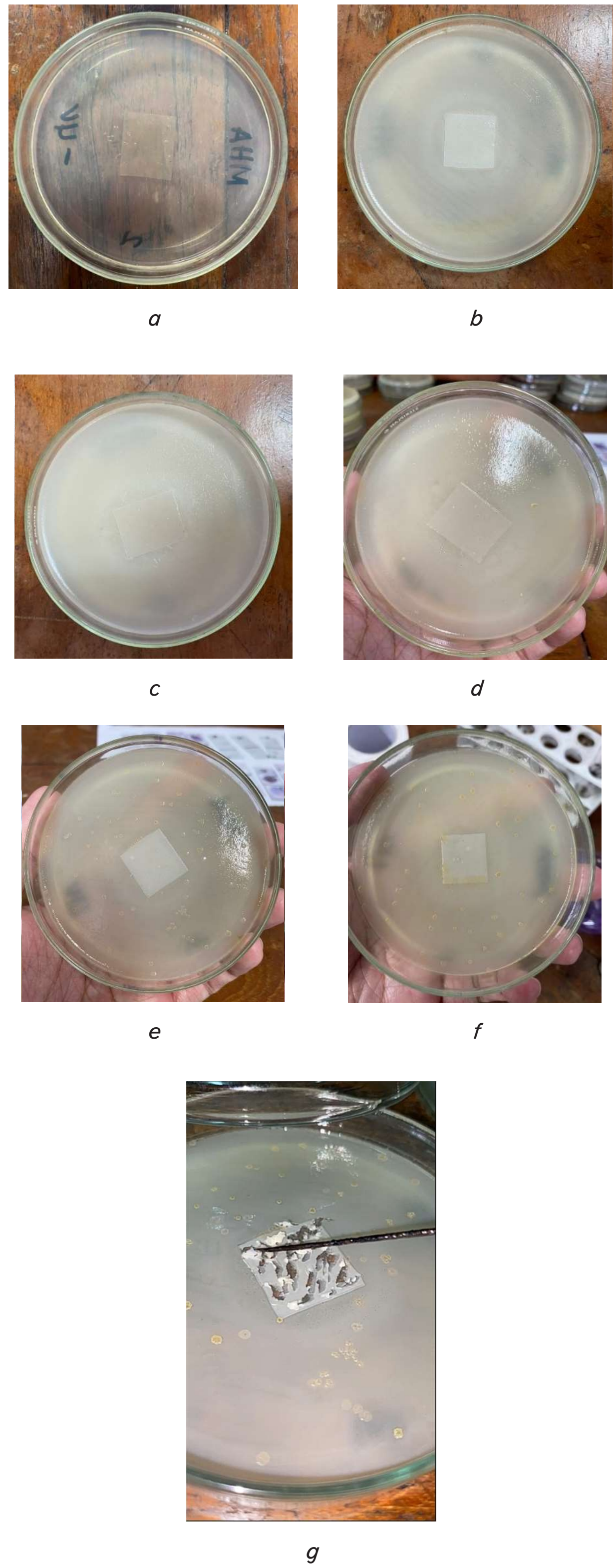


Fig. 4. Antimicrobial testing on samples of sago bioplastic: *a* – initial conditions; after incubation for *b* – 24 hours; *c* – 48 hours; *d* – 72 hours; *e* – 96 hours; *f* – 120 hours; *g* – 168 hours

thickness indicates the material's heightened vulnerability to extended periods of microbial presence.

The progression of bacterial growth observed over extended intervals, from 72 hours to 120 hours, unveils valuable insights into the bioplastic material's interaction with microorganisms and its susceptibility to microbial colonization. At the 72-hour mark, as depicted in Fig. 4, *d*, a continuation of the trend seen in earlier observations is evident. Bacterial colonies on the bioplastic sheet have grown thicker, and the size of the bioplastic attached to the agar surface appears to have reduced. This suggests an ongoing microbial activity and a potential impact on the structural integrity of the bioplastic.

A notable development emerges as the observation period extends to 96 hours, as seen in Fig. 4, *e*. In addition to the thickening of bacterial colonies, an intriguing occurrence occurs bubbles or foam formation on the bioplastic sheet. This phenomenon could indicate various processes, such as bacterial metabolic activity or the release of gases due to microbial interactions with the bioplastic surface. It underscores the complexity of microbial behavior on the material. By the 120-hour mark, shown in Fig. 4, *f*, further changes come to light. Additional bacterial growth is observed on the agar media and the surface of the bioplastic plate. This phenomenon might be attributed to other bacteria that were initially attached to the media during earlier observations. This observation underscores microbial communities' dynamic and ever-evolving nature and interactions within the testing environment. The seventh day of observation, as depicted in Fig. 4, *g*, marked a significant milestone in the bacterial testing of the bioplastic material. It clearly illustrated the transformative effects of prolonged microbial exposure on the material's properties and integrity.

6. Discussion of the experiment using Tawaro environmentally friendly sago starch as a sago bioplastic

Phosphorus pentoxide, or P_2O_5, is an element that exists in multiple crystallized forms or polymorphs. These forms are metastable states. Phosphorus pentoxide is utilized in numerous applications, such as serving as a desiccant and dehydrating agent and producing phosphoric acid. The presence of P_2O_5 in Tawaro sago starch could be attributed to the extraction process or environmental factors. It is crucial to recognize that P_2O_5 is different from heavy metals like Mercury (Hg), Lead (Pb), Cadmium (Cd), and Chromium (Cr_{6+}), which are widely recognized as environmental pollutants and can pose health hazards if present in excessive quantities. Magnesium sulfate (Mg_2O_4), commonly referred to as Epsom salt, is a compound with a wide range of external and internal applications [22]. Magnesium sulfate is widely utilized in bath salts due to its calming and healing attributes.

Additionally, it is employed in agriculture as a supplement for plant nutrition, providing magnesium and sulfur. The presence of it in this context could potentially be linked to soil or processing conditions. It is important to note that it does not fall under heavy metals. In addition, it is essential to note that the elements oxygen (O), carbon (C), and hydrogen (H) play a crucial role as constituents of the compound $O_{12}C_{92}H_{80}$ (Fig. 2, *b*). These elements are essential components of organic matter and can be found extensively throughout the natural world. The statement suggests that the substances are not classified as heavy metals. The presence of elements or compounds like P_2O_5 and Mg_2O_4 in Tawaro sago starch does not necessarily indicate contamination by heavy metals linked to environmental pollution. The differentiation between different types of sago starch is crucial to guarantee its safety and appropriateness for various uses.

The mention of the SNI (Indonesian National Standard) standard implies that Tawaro sago starch fulfills the requirements to serve as a viable bioplastic foundation for food packaging. The statement supports the worldwide movement towards sustainable and eco-friendly packaging options, emphasizing the preference for natural materials over synthetic ones [23]. The use of raw materials in food packaging has become increasingly popular due to the increasing demand for packaging options that are environmentally friendly and sustainable [17, 24].

The analysis of mechanical properties testing performed on sago bioplastic material sheets (Metroxylon SP) has provided valuable insights into how the material reacts to UV exposure. The results provide a detailed understanding of the impact of UV treatment on the elasticity modulus of the sheet. After conducting a thorough analysis of the obtained results, it is evident that applying UV exposure treatment can modify and improve the elongation properties of the sheet material when exposed to external forces. It is important to highlight that there is a significant exception observed in the case of specimen D3UV72. In this particular instance, extended exposure to UV light seems to result in a decline in the material's mechanical properties. This suggests that there is a point at which prolonged UV exposure may start to have fewer positive effects or even negative effects on the material's performance. Using a UV light source, a high-frequency light wave with a 100–280 nm wavelength and an energy of 375 kJ/mol. Exposure to UV radiation can change the molecular bonds in the sample [25].

The study reveals an interesting finding in specimen D2UV48, as the mechanical properties demonstrate a noteworthy improvement. The elastic modulus experienced a significant increase from 1,097 N/mm^2 to 2,867 N/mm^2, indicating a remarkable 161 % growth, as illustrated in Fig. 5. The discovery highlights the complex connection between UV exposure and the mechanical characteristics of sago bioplastic samples. The period of UV exposure lasting between 24 to 42 hours is considered a critical window, as it significantly improves the material's mechanical performance. The increased mechanical properties observed can be explained by the chemical changes that occur due to UV exposure. Oxygen, which is likely introduced through photochemical reactions, can potentially cause changes in the chemical composition and cross-linking of the sample surface. The suggested modifications can potentially strengthen the substance, improving its structural soundness.

Extended UV exposure, as seen in specimen D3UV72 (2.211 N/mm^2), provides valuable insights into the behavior of sago bioplastics throughout time. Extended UV exposure slows the lengthening of these bioplastic specimens, indicating a more progressive mechanical property change. UV-induced biodegradation of bioplastics is linked to this phenomenon. Oxidation drives biodegradation. UV radiation causes chemical reactions in sago bioplastics, polymerizing polymer chains. UV-generated free radicals catalyze these processes. UV light-induced chlorine-hydrogen interactions are crucial to this chain reaction. The interaction between elements gradually transforms bioplastic material, changing its mechanical characteristics.

Note that the decrease in elongation from D2UV48 to D3UV72 is safe. The SNI standard [21] requires tensile elongation at break to be less than 5 % after 250 hours of UV irradiation. The variations in elongation found in these specimens are well within acceptable boundaries, showing that the material is mechanically adequate for its intended applications even after extensive UV exposure. Biodegradability is important in situations where cost-effective disposal is a requirement after use [26]. Sago bioplastics are environmentally friendly alternatives to traditional plastics, which promotes sustainability and responsible material use.

Sago bioplastic's antimicrobial qualities, particularly its capacity to inhibit bacteria and fungal development, are assessed by microbial growth testing on its surface. This study uses Bacillus subtilis as the test bacteria. Bacillus subtilis is a gram-positive rod bacterium that measures 2–3 nanometers long and 0.7–0.8 nanometers wide. These bacteria is important in the nutrient cycle because it is saprophytic and thrives on decaying organic materials. Its ability to produce a variety of enzymes makes it useful in many industrial applications [16, 27]. Industry uses Bacillus subtilis to make proteases, amylases, antibiotics, and compounds. Bacillus subtilis is experienced in environmental cleanup, especially chromium removal. This bacterium detoxifies or sequesters heavy metals alone or in groups [28]. Its ability to reduce heavy metal contamination highlights its versatility and environmental importance.

During the 96-hour bacterial test of the bioplastic sheet, it was observed that bubbles or foam formed (Fig. 4, *e*). Multiple factors contribute to this phenomenon, which can be attributed to the characteristics of bioplastic materials and their interactions with bacteria. These factors include the production of gas by bacteria, the release of gas from the material, the metabolic activity of bacteria, chemical interactions, material deformation, and variations in pressure and temperature. The same idea was conveyed by the source referenced as [29]. The presence of bubbles or foam in bacterial tests conducted on bioplastic materials should be interpreted with caution, as its significance can vary depending on the specific objectives of the test and the desired properties of the material.

Bacterial testing on bioplastic material containing sago starch indicated optimum bacterial growth on the whole surface of the plate, with no growth inhibitors that could prevent Bacillus subtilis bacteria from growing. Bioplastic plates contain sago starch, which bacteria use to build colonies. Bacteria may decompose bioplastics, making them eco-friendly. After piercing and raising, the material became brittle (easily torn) on the seventh day *(*Fig. 4, g) due to increased bacterial activity. According to SNI criteria [21], product surface microbial growth is >60 % for one week. Fig. 4, *b* shows that 100 % of bacteria filled the sago bioplastic specimen in two days. Because bioplastics are natural starches with protein, young bacteria proliferate by defending themselves.

The research could encounter limitations in terms of the conversion of sago starch into bioplastics. This process may require specialized equipment and expertise, which could restrict its scalability and practicality for small-scale operations or resource-constrained regions. A thorough evaluation of the cost of sago-based bioplastics, encompassing raw material acquisition and processing, is necessary. The potential limitation of adopting bioplastics could be attributed to their higher price than conventional plastics. Various factors, including the specific region, climate, and cultivation practices, influence sago starch quality and characteristics. The variability in material properties can challenge maintaining consistency during bioplastic production.

Several disadvantages related to the study can be observed alongside potential approaches for mitigating them in future research. One of these disadvantages is the diversity in sago starch characteristics resulting from geographical and agricultural disparities, which can impact the uniformity of the material. In order to effectively tackle this issue, future research endeavors could entail establishing partnerships with specialists in sago farming to enhance the quality of starch and formulate uniform procedures. The issue of variability in the rates of biodegradation of sago-based bioplastics can be effectively mitigated by implementing formulation optimization techniques and conducting standardized biodegradation testing across diverse environmental conditions. This approach ensures the attainment of consistent and predictable degradation patterns. Reducing costs associated with sago-based bioplastics can be achieved by implementing process optimization techniques and undertaking scale-up initiatives. Subsequent investigations may prioritize enhancing production efficiency and exploring sourcing and processing technologies that are economically advantageous. To mitigate this drawback, forthcoming research endeavors may undertake more extensive life cycle analyses, wherein sago-based bioplastics are compared to a broader spectrum of conventional plastics and alternative bioplastic materials. This approach would yield a more precise evaluation of the environmental implications associated with sago-based bioplastics.

The study's development encompasses multiple stages and avenues for further research and progress. One such direction is to improve the bioplastic formulation to enhance its material properties, including tensile strength, flexibility, and barrier properties. To achieve the desired characteristics, adjusting the ratios of sago starch, glycerol, and activator solution may be necessary. Conduct research on novel processing techniques to optimize the conversion of sago starch into bioplastics, focusing on methods that enhance efficiency and streamline the overall production process. One potential avenue for improvement and expansion is the exploration of innovative approaches, such as extrusion or 3D printing, which have the potential to enhance efficiency and scalability. The objective is to establish a consistent set of sago starch properties by addressing the variability caused by geographical and cultivation variations. Collaboration with sago cultivators is necessary to establish uniform quality standards. Research sustainable sago cultivation practices that reduce environmental impact, such as implementing agroforestry or organic farming techniques. Evaluate the environmental impact of expanding sago cultivation.

The study will likely face numerous difficulties and challenges in different areas, including the variation in sago starch properties caused by geographical factors and cultivation practices. The variability in sourcing and the need for consistent raw material quality may present challenges. Converting sago starch into bioplastics can be challenging due to the requirement of specialized equipment and expertise. This may result in processing difficulties, scalability issues, or the necessity for expensive modifications. Developing an optimized bioplastic formulation that balances material properties can be complex and intricate. A significant challenge is to balance factors such as starch content, plasticizer ratio, and activator solution composition. Conducting biodegradation studies requires careful attention to experimental setups and extended observation periods to assess the effects of different environmental conditions accurately. The process of standardizing these tests presents certain difficulties.

quickly on bioplastics. Microbial development must be assessed and managed for diverse applications since organic materials like sago bioplastic are susceptible to microbial activity. For several reasons, understanding sago bioplastic microbial growth speed is vital.

7. Conclusions

1. The absence of heavy metals within the composition was discovered by carefully investigating the XRD (X-ray diffraction) features of Tawaro-type sago bioplastic material, which is both promising and environmentally benign. This research further establishes sago-based bioplastics as a more environmentally friendly and sustainable alternative to petroleum-based plastics. A finding of this nature has far-reaching ramifications, especially in environmentally friendly packaging materials and other fields where preventing heavy metal contamination is critical.

2. Sago bioplastic's modulus of elasticity changed significantly when exposed to UV radiation. Under ultraviolet exposure for 48 hours, modulus of elasticity levels increased significantly from 1,097 N/mm^2 to 2,867 N/mm^2. UV light is responsible for this 161 % rise, demonstrating its tremendous effect on the substance. A complex chemical alteration in the bioplastic's chemical structure under ultraviolet exposure causes this metamorphosis. UV light modifies polymer chains by reactions. Changing the material's structure strengthens it, increasing modulus of elasticity.

3. Microbes on sago bioplastic evolve rapidly. Suitable temperature and humidity allow microbial colonies to grow quickly on bioplastics. Microbial development must be assessed and managed for diverse applications since organic materials like sago bioplastic are susceptible to microbial activity. For several reasons, understanding sago bioplastic microbial growth speed is vital.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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